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METEOROLOGISKA INSTITUTET
FINNISH METEOROLOGICAL INSTITUTE

RAPORTTEJA
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2017:4

13TH INTERNATIONAL WORKSHOP ON GREENHOUSE GAS MEASUREMENTS FROM SPACE

BOOK OF ABSTRACTS

P. T. VERRONEN (editor)

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13th International Workshop on Greenhouse Gas Measurements from Space

Book of Abstracts

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Meteorologiska institutet
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Title
13th International Workshop on Greenhouse Gas Measurements from Space, Book of Abstracts

Abstract

The **13th International Workshop on Greenhouse Gas Measurements from Space (IWGGMS)** will be held on 6-8 June, 2017, at the University of Helsinki in Helsinki, Finland. The workshop is organised by the Finnish Meteorological Institute with support from the University of Helsinki. The workshop gathers together more than 160 scientists from the EU, USA, Japan, China, Australia, Canada, and Russia. This report is the official abstract book of the workshop.

Background. Success in space-based global measurement of greenhouse gases, such as carbon dioxide and methane, is critical for advancing the understanding of carbon cycle. The recent developments in observations and in interpreting the data are very promising. Space-based greenhouse gas measurement, however, poses a wide array of challenges, many of which are complex and thus demand close international cooperation.

The goal of the workshop is to review the state of the art in remote sensing of CO_2, CH_4, and other greenhouse gases from space including the current satellite missions, missions to be launched in the near future, emission hot spots on regional and global scales, process studies and interactions of carbon cycle and climate, pre-flight and on-orbit instrument calibration techniques, retrieval algorithms and uncertainty quantification, validation methods and instrumentation, related ground-based, shipboard, and airborne measurements, and flux inversion from space based measurements.

The workshop is part of the programme for the centenary of Finland's independence in 2017.

The workshop is also one of the activities arranged by the Finnish Meteorological Institute to support Finland's chairmanship of the Arctic Council, 2017 - 2019.

The workshop is sponsored by the Finnish Meteorological Institute, the University of Helsinki, the European Space Agency, the City of Helsinki, the Federation of Finnish Learned Societies, and ABB Inc.

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Nimeke

13. kansainvälinen kasvihuonekaasujen kaukokartoituskokous, tieteellisten esitysten tiivistelmät

Tiivistelmä

Ilmatieteen laitos järjestää 13. kansainvälisen kasvihuonekaasujen kaukokartoituskokouksen 6.–8. kesäkuuta 2017 Helsingin yliopiston päärakennuksella yhteistyössä yliopiston kanssa. Kokoukseen osallistuu yli 160 tutkijaa EU-maista, Yhdysvalloista, Japanista, Kiinasta, Australiasta, Kanadasta ja Venäjältä. Tämä raportti sisältää kokouksessa pidettävien tieteellisten esitelmien tiivistelmät.

Taustaa. Kaukokartoitusmittalaitteilla tehtävät globaalit kasvihuonekaasuhavainnot ovat yhä tärkeämpiä hiilen kierron ymmärtämisen kannalta. Viimeaikainen kehitys niin mittauksissa kuin niiden tulkinnassakin antaa suuria lupauksia. Maata kiertävistä satelliiteista tapahtuvat mittaukset ovat kuitenkin monella tapaa haastavia, ja näiden monimutkaisten haasteiden ratkaiseminen vaatii kansainvälistä yhteistyötä.

Kokouksen tarkoitus on esitellä viimeisin tieto hiilidioksidin, metaanin ja muiden kasvihuonekaasujen kaukokartoituksesta. Aihepiiriin sisältyy mm. nykyiset ja tulevat satelliittihankkeet, kaasujen vuot alueellisesti ja globaalisti, prosessitutkimus ja vuorovaikutus ekosysteemien hiilen kierron ja ilmaston välillä, mittalaitteiden kalibrointi ennen ja jälkeen satelliitin laukaisun, mittausten käsittely matemaattisin algoritmein ja mittausvirheen määritys, validointimenetelmät ja -laitteet, muut esim. maan pinnalta, laivoista ja lentokoneista tehtävät mittaukset, sekä kaasujen lähteiden ja nielujen matemaattinen inversio kaukokartoitusmittauksista.

Kokous on osa Suomen itsenäisyyden satavuotisjuhlavuoden ohjelmaa.

Kokous on myös yksi Ilmatieteen laitoksen järjestämistä tapahtumista liittyen Suomen Arktisen neuvoston puheenjohtajuuskauteen 2017 - 2019.

Kokousta tukevat tieteellisesti ja taloudellisesti Ilmatieteen laitos, Helsingin yliopisto, Euroopan avaruusjärjestö, Helsingin kaupunki, Tieteellisten seurain valtuuskunta ja ABB Oy.

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Contents

FINNISH METEOROLOGICAL INSTITUTE

We at the Finnish Meteorological Institute are proud to host the 13th International Workshop on Greenhouse Gas Measurements from Space on 6th -8th June, 2017. The workshop will gather about 170 scientists worldwide to discuss the recent advances in space based greenhouse gas observations. The goals of the workshop are important in supporting actions to reduce greenhouse gas emissions to limit the climate change. In Finland we are, in particular, concerned on the arctic regions as the high northern latitudes are especially sensitive to climate change, indicated by above-average rising temperatures.

It is my pleasure to welcome you all to Helsinki, in particular this year when we celebrate the centenary of Finland's independence and we received the chairmanship of the Arctic Council. I wish you a very successful workshop on a topic where the international collaboration is more important than ever.

Prof. Juhani Damski
Director General
Finnish Meteorological Institute

The 13th International Workshop on Greenhouse Gas Measurements from Space is part of the programme for the centenary of Finland's independence in 2017.

Scientific organising committee (SOC)

Johanna Tamminen (chair)	Finnish Meteorological Institute	Finland
Tuula Aalto	Finnish Meteorological Institute	Finland
Ilse Aben	SRON	the Netherlands
Hartmut Boesch	University of Leicester	UK
Ugo Cortesi	CNR	Italy
David Crisp	NASA JPL	USA
Annmarie Eldering	NASA JPL	USA
Sander Houweling	Utrecht University	the Netherlands
Tsuneo Matsunaga	NIES	Japan
Yasjka Meijer	ESA	the Netherlands
Hibiki Noda	NIES	Japan
Justus Notholt	University of Bremen	Germany
Timo Vesala	University of Helsinki	Finland

FMI local organising committee (LOC)

Johanna Tamminen (chair), Tuula Aalto, Janne Hakkarainen, Seppo Hassinen, Iolanda Ialongo, Rigel Kivi, Ella Kivimäki, Otto Lamminpää, Hannakaisa Lindqvist, Aki Tsuruta, Simo Tukiainen, Pekka Verronen, and Kirsi Virolainen

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Finnish Meteorological Institute
University of Helsinki
European Space Agency
City of Helsinki
Federation of Finnish Learned Societies
ABB Inc.

List of invited presentations

Dr. David Crisp	Existing space-based greenhouse gas measurement capabilities and near-term plans
Prof. Yi Liu	Early phase achievement of TanSat
Prof. Martin Heimann	Quantifying regional biogeochemical budgets: the scientific challenges
Prof. Anna Michalak	Key opportunities and challenges in using space-based observations for greenhouse gas flux estimation at regional to global scales
Dr. Michael Buchwitz	Overview and latest results of ESA's GHG-CCI project and Copernicus Climate Change Service (C3S) operational continuation
Dr. Ying Sun	OCO-2 advances photosynthesis observation from space via solar-induced chlorophyll fluorescence

Agenda and daily schedule, version June 2nd, 2017

Photo: Samuli Siltanen

13th International Workshop on Greenhouse Gas Measurements from Space

on June 6 – 8, 2017

University of Helsinki, Pieni Juhlasali – Small Hall, Fabianinkatu 33, Helsinki

Invited presentations 20 + 5 min, Contributed presentations 12 + 3 min

Poster boards are in portrait format and can fit a poster up to a standard A0 size (841 x 1189 mm)

JUNE 6, 2017

TIME	PRESENTATION
09:00 to 09:15	**Opening Remarks, (TBD)**, Finnish Meteorological Institute
09:15 to 09:20	**Practical information, Johanna Tamminen**
09:20 to 10:30	**Session 1: Ongoing and near-term satellite missions and calibration (Chair Tamminen)**
09:20 (20+5min)	**Opening Talk: David Crisp**, NASA Jet Propulsion Laboratory, Overview on existing satellite measurement capabilities and near term plans
09:45 (12+3min)	**Matsunaga, T.:** Recent Progress in NIES GOSAT and GOSAT-2 Projects
10:00	**Landgraf, J.:** Sentinel 5 precursor and the TROPOMI shortwave infrared total column products
10:15	**Durak, O.B.A.:** Progress report from GHGSat-D: Towards commercial high spatial resolution CH_4 and CO_2
10:30 to 10:55	**Coffee**
10:55 to 12:05	**Session 1 continue: Ongoing and near-term satellite missions and calibration (Chair Eldering)**
10:55 (20+5min)	**Invited talk: Yi Liu,** Institute of Atmospheric Physics of Chinese Academy of Sciences, China, First observations of TanSat satellite
11:20 (12+3min)	**Bi, Y.M.:** TanSat ACGS instrument prelaunch performance evaluation of radiometric calibration
11:35	**Yang, Z .:** Preliminary assessment of TanSat Atmospheric Carbon Dioxide Grating Spectroradiometer on-orbit Performance
11:50	**Crisp, D.**: OCO-2: A progress report at the end of the prime mission
12:05 to 13:20	**Lunch**

13:20 to 15:15	**Session 4 – Part 1: Greenhouse gas observations for emission hot spots and flux inversions on regional and global scales (Chair Houweling)**
13:20 (20+5min)	**Invited talk: Anna M. Michalak,** Carnegie Institution for Science and Stanford University, USA, Key opportunities and challenges in using space-based observations for greenhouse gas flux estimation at regional to global scales
13:45 (12+3min)	**Crowell, S.:** Were Tropical Land Ecosystems a Source of CO_2 in 2015? The View from OCO-2 and GOSAT
14:00	**Hakkarainen, J.**: Direct space-based observations of anthropogenic CO_2 emission areas from OCO-2
14:15	**Lin, B.:** Regional atmospheric greenhouse gas distributions observed during ACT-America field campaigns
14:30	**Liu, J.:** Responses of tropical terrestrial biosphere carbon cycle to the 2015-2016 El Nino
14:45	**Wang, J.:** Chinese CO_2 fluxes inferred from OCO-2 and GOSAT and from in situ data during the 2015 El Nino event
15:00	**Butz, A.:** Remote sensing of volcanic CO_2, HF, HCl, SO_2, and BrO in the downwind plume of Mt. Etna
15:15 to 15:40	**Coffee**
15:40 to 16:55	**Session 2 – Part 1: Retrieval algorithms and uncertainty quantification (Chair Boesch)**
15:40 (12+3min)	**ODell, C.W.:** Recent improvements in XCO2 measurements from the Orbiting Carbon Observatory-2
15:55	**Natraj, V.:** Improved Orbiting Carbon Observatory-2 (OCO-2) Retrievals Using a BRDF Model for the Surface
16:10	**Braverman, A.:** Uncertainty quantification for OCO-2 remote sensing retrievals via Monte Carlo simulation
16:25	**Serio, C.:** Assessment of a physically-based simultaneous retrieval for CO_2, Ch_2 and N_2O from IASI observations and inter-comparison with in situ observations and AIRS, GOSAT, OCO-2 satellite products
16:40	**Xiong, X.: CO_2**, CH_4 and CO Retrievals and Validation at NOAA using CrIS on S-NPP and JPSS-1
16:55 to 17:00	**Short break**
17:00 to 18:15	**General discussion on requirements of future greenhouse gas missions (Discussion led by D. Crisp)**
18:30 to 20:00	**Icebreaker – Säätytalo – State of Estates, Snellmaninkatu 9-11 , Helsinki (walking distance from the meeting room)**

JUNE 7, 2017

TIME	PRESENTATION
09:00 to 10:25	**Session 5 – Global observations of greenhouse gases for process studies and interactions of carbon cycle and climate (Chair Aben)**
09:00 (20+5 min)	**Invited talk**: **Martin Heimann**, Max Planck Institute for Biochemistry & Univ. Helsinki, Quantifying regional biogeochemical budgets: the scientific challenges
09:25 (12+3 min)	**Bloom, A.A**.: Atmospheric CO2 constraints on tropical carbon cycle processes
09:40	**Detmers, R.G.:** RemoTeC GOSAT retrievals and the 2011 La Nina: Terrestrial CO_2 flux variations over the Southern Hemisphere
09:55	**Parker, R.J.:** Assessing the inter-annual variability of wetland methane emissions
10:10	**Nechita-Banda, N.:** A joint CO-CO_2 inversion system for studying the effect of drought on the carbon cycle
10:25 to 10:35	**Coffee**
10:35 to 12:15	**Poster session (posters with odd numbers)**
12:15 to 13:45	**Lunch**
13:45 to 14:40	**Session 2 – Part 2: Retrieval algorithms and uncertainty quantification (Chair Cortesi)**
13:45 (20+5 min)	**Invited talk: Michael Buchwitz,** Institute of Environmental Physics of the University of Bremen, Germany, Overview and latest results of ESA's GHG-CCI project and Copernicus Climate Change Service (C3S) operational continuation
14:10 (12+3min)	**Gordon, I.:** Highlights of the HITRAN2016 database
14:25	**Yang, D.:** TanSat retrieval algorithm and its application on global carbon monitoring from space
14:40 to 15:40	**Session 4 – Part 2: Greenhouse gas observations for emission hot spots and flux inversions on regional and global scales (Chair Matsunaga)**
14:40 (12+3 min)	**Nassar, R.:** Quantifying CO_2 emissions from individual coal power plants using OCO-2 observations
14:55	**Weir, B.:** Disentangling GEOS model biases from those of retrieved column carbon dioxide
15:10	**Saigusa, N.:** Monitoring carbon cycle change using an integrated observation, modeling and analysis system
15:25	**Stanevich, I.:** Characterizing atmospheric transport errors in models using GOSAT XCH_4 retrievals
15:40 to 16:05	**Coffee**
16:05 to 17:20	**Session 3 – Part 1: Validation and supporting observations including ground based, aircraft and in situ observations (Chair Meijer)**
16:05 (12+3 min)	**Camy-Peyret, C.:** Thermal infrared measurements of CO_2 from IASI over the Arctic Ocean in summer and comparison with the CAMS CO_2 inversion product
16:20	**Houweling, S.:** Bias correction in CH4 flux inversions using satellite data and the role of atmospheric transport
16:35	**Masiello, G.:** Validation of physical inverse products from IASI spectra: the case of Carbonyl Sulphide (OCS)
16:50	**Nagel, J.:** GreenLITE(TM): A Novel Approach to Ground-Based Quantification and Mapping of Greenhouse Gases with Potential for Validation of Low Bias Lidar Measurements Needed for Space
17:05	**Kivi R.:** FTS measurements of Greenhouse gases over Sodankylä

JUNE 8, 2017

TIME	PRESENTATION
09:00 to 09:45	**Session 3 – Part 2: Validation and supporting observations including ground based, aircraft and in situ observations (Chair Aalto)**
09:00 (12+3 min)	**Bovensmann, H.:** Using airborne remote sensing observations to determine emissions of complex CH4 and CO2 localised sources
09:15	**Mao, J.:** Atmospheric CO_2 Concentration Measurements to Cloud Tops from an Airborne Lidar
09:30	**Suto, H.:** Airborne-based demonstration of intelligent pointing onboard GOSAT-2
09:45 to 09:55	**Short break**
09:55 to 10:50	**Session 6 – Solar induced fluorescence for identifying natural sources and sinks (Chair Noda)**
09:55 (20+5 min)	**Invited talk: Ying Sun,** Soil and Crop Sciences Section, Cornel University, Ithaca, USA, OCO-2 advances photosynthesis observation from space via solar-induced chlorophyll fluorescence
10:20 (12+3 min)	**Norton, A.J.:** Using solar-induced chlorophyll fluorescence (SIF) to constrain global gross primary productivity in the process-based terrestrial biosphere model BETHY-SCOPE
10:35	**Xiao, X.:** Seasonal dynamics and inter-annual variation of solar-induced chlorophyll fluorescence and gross primary production in North, Central, and South America during 2000-2016
10:50 to 11:00	**Group photo**
11:00 to 11:10	**Coffee**
11:10 to 12:30	**Poster session (posters with even numbers)**
12:30 to 13:50	**Lunch**
13:50 to 15:50	**Session 7 – Future missions and observing strategies (Chair Crisp)**
13:50 (12+3 min)	**Eldering, A.:** The OCO-3 Mission: Updated Overview of Science Objectives and Status
14:05	**Buisson, F.:** An Update of MicroCarb project progress and perspective
14:20	**Meijer, Y.J.:** State of play for a European operational monitoring system for fossil CO_2 emissions
14:35	**Moore, B.M. :** The GeoCarb Mission
14:50	**Ott, L.:** NASA's Carbon Cycle OSSE Initiative - Informing future space-based observing strategies through advanced modeling and data assimilation
15:05	**Dinelli, B.M**.: OXYCO2: A New Experiment for the Measurement of the CO_2 Distribution in the Stratosphere and the Upper Troposphere
15:20	**Pierangelo, C.:** Status of MERLIN mission
15:35	**Rayner, P.J.:** The Role of CO observations in source attribution for the GEOCARB Mission
15:50 to 16:10	**Coffee**
16:10 to 17:00	**Wrap up of meeting outcomes and discussions**
16:10	**Discussion / all**
16:35	**Wrap up by 13th IWGGMS Scientific Organizing Committee**
16:50	**Presentation by the host of 14th IWGGMS**
17:00	**Adjourn**

POSTERS

Session1

NUMBER	POSTER
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1.7	**Kataoka, F.:** Inter sensor comparison between GOSAT and OCO-2 spectral radiance and retrieved carbon dioxide
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1.10	**Lichtenberg,** G.: SCIAMACHY: Spectral Calibration in the SWIR Channels
1.13	**Payan, S.:** Comparison of thermal infrared measurements of CO2 from GOSAT and IASI over the Arctic Ocean in summer
1.14	**Pradines, D.:** Overview of MicroCarb operations concepts
1.15	**Wang, Q.:** Prelaunch Spectral Calibration of the TanSat's Atmospheric Carbon Dioxide Grating Spectroradiometer

Session2

NUMBER	POSTER
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2.3	**Bril, A.:** EOF-based XCO2/XCH4 retrieval algorithm: Towards global GOSAT data processing
2.5	**Chen, X.:** Analysis of aerosol information content in CAPI/TanSat observation over land and induced error in CO2 retrieval from aerosol
2.6	**Dinelli, B.M.:** AIRWAVE: an algorithm for the retrieval of the total column of water from the measurements of the ATSR series and Sentinel 3/SLSTR
2.8	**Hashimoto, M.:** Accelerated aerosol retrieval algorithm MWPM-EXAM for GOSAT/TANSO-CAI and GOSAT-2/TANSO-CAI-2
2.9	**Kangah, Y.:** Study of IASI nitrous oxide (N2O) retrievals: application to long-range transport during the Asian summer monsoon
2.10	**Kulawik, S.S.:** Validation of OCO-2 and ACOS-GOSAT using HIPPO and TCCON
2.11	**Lamminpää, O.:** Dimension reduction methods for remote sensing of methane profile
2.13	**Nelson, R.R.: Usi**ng GEOS-5 Aerosols to Inform the OCO-2 CO2 Retrieval
2.15	**Payne, V.H.:** Spectroscopy for remote sensing of greenhouse gases: Recent advances and outstanding issues
2.16	**Ramanathan, A.K.:** CO2 Sounder Multiwavelength Lidar Measurements: Retrievals, Spectroscopy, Biases and Vertical Information
2.18	**Someya, Y.:** Ammonia detection using TIR band of GOSAT
2.19	**Somkuti, P.:** Implementing a PCA-based Fast Radiative Transfer Method for XCO2 Retrievals
2.20	**Sundström, A.-M.:** Assessment of the aerosol induced biases in the ESA Greenhouse Gas CCI satellite CO2 products
2.22	**Yamada, A.:** The impact on CH4 retrieval of GOSAT/TANSO-FTS TIR band from differences in line parameter databases and from the uncertainty of the continuum absorption
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Session 3

NUMBER	POSTER
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3.2	**Boesch, H.:** Towards a UK TCCON Station
3.5	**D'Amato, F.:** Terrestrial and airborne optical analyzers for the detection of greenhouse gases
3.6	**Deutscher, N.M.:** Comparison of XCO2 and XCH4 measurements from three solar FTIR instruments at Wollongong
3.7	**Dils, B.:** The CCI-GHG CRDP#4 : Validation using TCCON
3.8	**Hochstaffl, P.: V**alidation of Carbon Monoxide Total Columns from SCIAMACHY mission with

NDACC/TCCON

3.11	**Kivi, R.:** Fiducial Reference Measurements for Ground-Based Infrared Greenhouse Gas Observations (FRM4GHG) campaign at the Sodankylä TCCON site
3.12	**Laurila, T.:** Integrated Carbon Observation System (ICOS) Research Infrastructure provides atmospheric GHG data for scientist
3.13	**Lindqvist, H.:** Assessment of the satellite-measured seasonal cycles of XCO2 from GOSAT and OCO-2
3.16	**Morino, I.:** Philippines TCCON installation: towards quantifying atmospheric carbon in Southeast Asia
3.18	**Natraj, V.:** Aerosol Scattering Effects on Water Vapor Retrievals over the Los Angeles Basin
3.19	**Qin, X.C.:** Ground-based measurement of column-averaged mixing ratios of carbon dioxide in Tokyo by a portable optical spectrum analyzer
3.20	**Roehl, C.M.:** Update on OCO-2 Validation Using TCCON
3.21	**Saitoh, N.:** Validation of Level 2 CO2 and CH4 products of GOSAT/TANSO-FTS thermal infrared band and future algorithm improvement
3.23	**Tukiainen, S.: V**ertical distribution and time-series of Arctic methane
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3.25	**Velazco, V.A.:** Validation of GOSAT Products in the Southern Hemisphere: Alice Springs Desert M-Gain Comparisons
3.26	**Yue, T.X. :** An Introduction to a Carbon Verification System for TanSat

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NUMBER	POSTER
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4.21	**Tsuruta, A.:** Towards assimilation of XCH4 GOSAT observations to global CH4 emission estimates by CTE-CH4 data assimilation system
4.24	**Yang, S.:** Monitoring Anthropogenic CO2 Emissions by the Seasonal Changes of Atmospheric Xco2 from Satellite Observations
4.25	**Zadvornykh, I.V.:** The joint methane retrieval from GOSAT SWIR and TIR spectra over Western Siberia

Session 5

NUMBER	POSTER
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5.6	**Laeng, A.:** Global CFC-11, CFC-12, HCFC-22, CCl4, CH4, N2O measurements with MIPAS: validation, climatologies and trends
5.7	**Murakami, K.:** High Resolution Global Terrestrial Carbon Flux: Evaluations and Applications
5.10	**Shi, Y.:** Relationship between biomass burning emissions and GOSAT XCO2 and MOPITT CO changes over fire affected regions
5.11	**Tamminen, J.:** Carbon Balance under Changing Processes of Arctic and Subarctic Cryosphere (CARB-ARC project)
5.12	**Wei, J.:** GES DISC Greenhouse Gas Datasets and Associated Services

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NUMBER	POSTER
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6.3	**Oshio, H.:** Radiance offset correction for observing solar-induced chlorophyll fluorescence from GOSAT
6.5	**Thum, T.:** Assessing seasonal cycle of photosynthesis by solar induced fluorescence in Fenno-Scandinavia

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7.5	**Julien, E.:** Level 2 processing of MERLIN mission data
7.6	**Kawa, S.R.:** Updated Global Error Characterization for a CO2 Lidar Space Mission
7.7	**Landgraf, J.:** The spectral sizing of ESA's future CO2 observing space mission
7.10	**Nassar, R.:** Recent studies on high latitude greenhouse gas observations from a highly elliptical orbit (HEO) mission
7.14	**Saito, M.:** GOSAT observations and global carbon cycle
7.15	**Sierk, B.:** Elements of a future Sentinel mission for imaging fossil fuel CO2 emissions
7.16	**Tirelli, C.:** Advanced tropospheric ozone monitoring by data fusion and assimilation

1 Ongoing and Near-Term Satellite Missions and Calibration

TanSat ACGS instrument prelaunch performace evaluation of radiometic calibration

YanMeng Bi, Zhongdong Yang, Qian Wang, Songyan Gu
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TanSat is a key satellite mission of China Earth Observation programme, which is designed to measure global atmospheric column-averaged CO2 dry air mole fraction (XCO2) using the spectroradiometer of visible and near infrared solar reflected spectrum. Here, we describe the prelaunch radiometric calibration of TanSat's instrument in terms of its dark current response, gain coefficients, single to noise ratios. The preliminary mode of dark current response with temperature for two CO2 bands has been built based on the 12 blacked pixels on the two sides of the array, and planned to be updated on orbit using dark current measurements mode. The SNR of each channel met the mission requirements for O2 A-band and weak CO2 band, but slightly missed the requirement in a few of channels in the SCO2 band. The gain coefficients modes of three bands were very stable across the entire focal plane array, and hold a negligible random error component. The second order gain coefficients are smaller five orders of magnitude than the first order gain coefficients, and more high order gain coefficients are smaller more orders of magnitude in each channel of all three bands. It suggested that the instrument had significant response linearity. All of these results show smaller errors of radiometric calibration. The accuracy of prelaunch radiometric calibration satisfies the preflight absolute calibration uncertainty requirement of 5%.

An Update of MicroCarb project progress and perspective.

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MicroCarb is a European initiative for the monitoring of the CO2 fluxes and a better understanding of the mechanisms that control these fluxes. It will provide atmospheric CO2 concentrations data to the scientific community, in the continuation or in parallel to the ongoing operational programs (GoSat, OCO, Tansat).
The Microcarb instrument is a grating spectrometer that acquires high-resolution spectra in 4 bands between 0.76µ and 2.1 µm. It will fly on board a micro satellite with a mass lower than 200 kg and will offer performances in line with the standards for CO2 measurements (ie 1ppm accuracy). Together with the requirement for a cost effective development, the compactness is made possible by an innovative optical design. Compared to previous mission with similar objectives, a specific innovation is the use of an additional spectral band at 1.27 µm (O2 absorption) that may allow a better normalization of the CO2 column, provided the airglow can be accounted for.
The project is conducted by the CNES in partnership with the UK Space Agency, and involves the scientific community from both France and UK.
Microbar project has now completed its preliminary design phase (phase B), is firmly decided, and is starting the realization phase.
The presentation will describe the progress of the project, its organization and will provide guidelines for the future. It will present the technical status with emphasis on the original aspects of the design, particularly regarding the instrument. The main budgets and a status of performances will be presented.

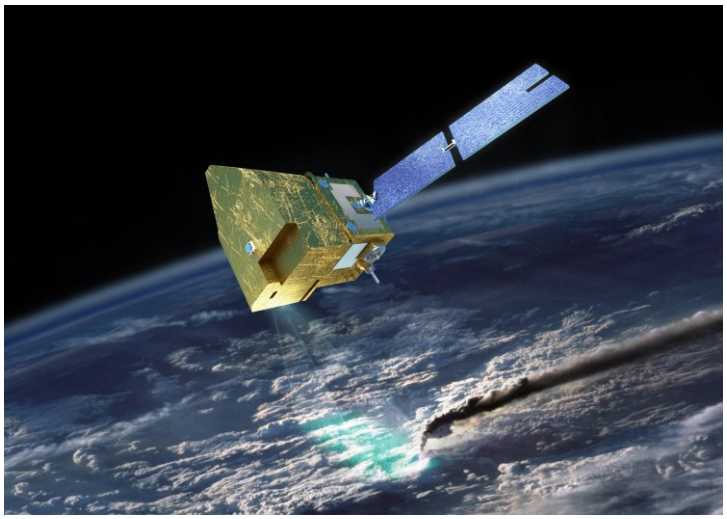

Figure 1: *Artist view of MicroCarb*

Existing space-based greenhouse gas measurement capabilities and near-term plans

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Space based sensors are providing new tools for studying atmospheric carbon dioxide (CO_2), methane (CH_4) and other greenhouse gases (GHGs). The Japanese Greenhouse gases Observing SATellite, GOSAT, has been operating since 2009, returning up to a thousand high-spectral-resolution measurements of reflected sunlight in cloud-free skies each day. These spectra are analyzed to estimate the column-averaged dry air mole fractions of CO_2 (X_{CO2}) and CH_4 (X_{CH4}) with single-sounding precisions and regional scale biases near 0.5% (~2 ppm X_{CO2}, ~10 ppb X_{CH4}). In July 2014, GOSAT was joined by NASA's Orbiting Carbon Observatory-2 (OCO-2). OCO-2 is now returning ~100,000 clear-sky estimates of X_{CO2} each day with single sounding random errors near 0.5 ppm (0.125%), and regional scale biases typically < 1 ppm. GOSAT and OCO-2 data are also returning estimates of solar induce chlorophyll fluorescence (SIF), which provides a sensitive indicator of CO_2 uptake by the land biosphere.

While these new measurements are providing new insights into the carbon cycle and its response to interannual variations in the climate, such as the intense 2015-2016 El Niño, they are also posing new challenges for regional-scale flux inversion experiments. The most significant of these are small (< 1 ppm), spatially coherent biases that can be misinterpreted as evidence for fluxes. In addition, limitations in the precision, spatial resolution and coverage restrict their use from monitoring emissions from cities or other discrete sources. These limitations must be addressed before the spatial resolution and coverage of the space-based datasets can be fully exploited.

To date, the Total Carbon Column Observing Network (TCCON) has served as the primary standard used to identify and correct systematic, regional-scale biases in the GOSAT and OCO-2 products. TCCON data have also provided insights into environmental conditions and retrieval algorithms shortcomings that contribute to bias, facilitating the development of effective bias correction algorithms. The TCCON measurement network may have to be expanded and other types of surface, tower, and airborne measurements may be needed to further identify and correct subtle biases in the space based GHG products.

The resolution and coverage limitations of the current measurements will addressed to some extent by the evolving fleet of space-based GHG sensors. In December of 2016, China's TanSat was successfully launched. Once in operation, its instruments will measure X_{CO2} and aerosols with capabilities expected to be intermediate between those of GOSAT and OCO-2. TanSat will be joined later this year by the Chinese Gaofen 5 (GF-5), which is designed to measure X_{CO2} and X_{CH4}. Sentinel 5p will also be launched this year, carrying TROPOMI, which will create 2-d maps of X_{CH4} with a spatial resolution of 7 km by 7 km. GOSAT-2, which is scheduled for launch in late 2018, will measure X_{CO} as well as X_{CO2} and X_{CH4}. That same year, OCO-3 is scheduled for deployment on the International Space Station (ISS). From the precessing orbit of the ISS, OCO-3 can collect X_{CO2} and SIF measurements from dawn to dusk. CNES recently approved the X_{CO2} mission, MicroCarb, for a 2020 launch, followed by the CNES/DLR X_{CH4} lidar mission, MERLIN, in 2021.
Besides Sentinel 5p, all of the sensors listed above are "sampling" systems rather "mapping" systems. The first geostationary carbon mapping system is NASA's GeoCarb mission, which will be deployed above North America around 2021. Future high-resolution GHG mapping missions in low Earth orbit are being considered by the Japanese (GOSAT-3) and European Copernicus program. Those missions will have launch dates in in the early to mid-2020's and could dramatically improve the spatial resolution and coverage.

OCO-2: A progress report at the end of the prime mission

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The NASA Orbiting Carbon Observatory-2 (OCO-2) completed its 2-year prime mission on October 16, 2016 and began its first extended mission. Since 6 September 2014, its 3-channel imaging grating spectrometer have been routinely returning almost one million soundings over the sunlit hemisphere each day. Between 5 and 13% of these soundings are sufficiently cloud free to yield spatially resolved estimates of the column-averaged CO_2 dry air mole fraction, X_{CO2}, with single-sounding random errors near 0.5 ppm at solar zenith angles as large as 70°. Another product derived from the OCO-2 spectra, solar induced chlorophyll fluorescence (SIF), is yielding insight into CO_2 uptake by the land biosphere.

The timing of the OCO-2 prime mission provided a unique opportunity to observe the response of the carbon cycle to changes in the tropical climate associated with the 2015-2016 El Niño. OCO-2 measurements clearly resolve variations in tropical-ocean outgassing (Chatterjee et al., 2017) as well as changes in the CO_2 uptake and release by tropical forests associated with drought, temperature stress, and fires (Liu et al., 2017; Heymann et al. 2017). OCO-2 measurements are providing new insight into the detectability of anthropogenic sources of CO_2 from space-based measurements of X_{CO2}. For example, Schwandner et al. (2017) find differences between Los Angeles and the background that range from ~4.4 to 6.1 ppm +/- 1 ppm, depending on season and atmospheric conditions. In a larger scale study, Hakkarainen et al. (2016) studied three regions of the world using OCO-2 X_{CO2} measurements, OMI NO_2 measurements, and the ODIAC inventory to produce maps of CO_2 anomalies associated with anthropogenic CO_2 emissions. They found that OCO-2 detects CO_2 enhancements in most populated regions where ODIAC predicts emissions greater than 0.5 $gC/m^2/day$.

To exploit the high volume of precise measurements returned by OCO-2, the OCO-2 team implemented innovative calibration methods, gas absorption spectroscopy, remote sensing retrieval algorithms and CO_2 flux inversion models. The end-to-end performance of the instrument and retrieval algorithm is continuously validated though comparisons with X_{CO2} estimates from TCCON (Wunch et al., 2017) and other standards. After correcting known biases in the OCO-2 X_{CO2} products, the median difference between co-located OCO-2 and TCCON X_{CO2} estimates is less than 0.4 ppm and the root-mean-square (RMS) differences are typically less than 1.5 ppm. However, there are still a few regions that show larger biases, the most significant of which is a +3 ppm bias over the ocean at mid and high latitudes during southern winter that has been attributed to the omission of stratospheric aerosols in the retrieval algorithm's state vector (O'Dell et al. 2017). These and other biases are being addressed with improved radiometric calibration tables, updated gas absorption cross-sections, inclusion of stratospheric aerosols in the prior, an updated surface reflectance model for land and other updates. An improved data product that includes these updates, version 8, will be produced during the summer of 2017.

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Progress report from GHGSat-D: Towards commercial high spatial resolution CH4 and CO2 plume imaging and quantification using a Fabry-Perot SWIR imaging spectrometer from a LEO nanosatellite

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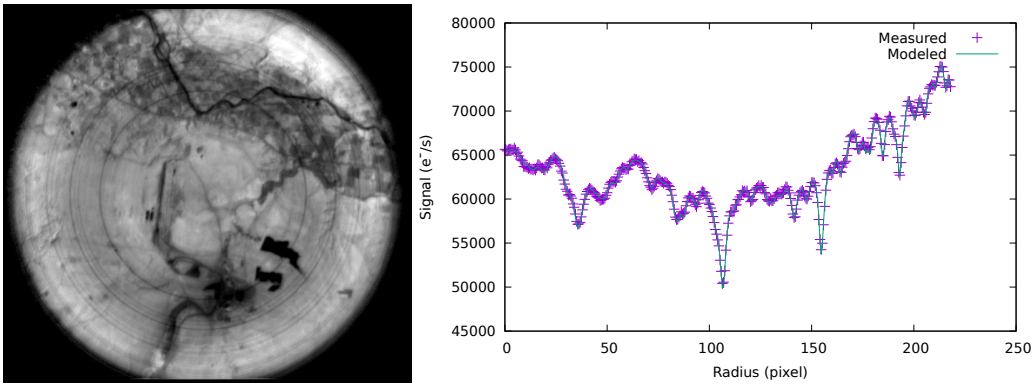
GHGSat-D (or "Claire") is GHGSat, Inc.'s demonstration greenhouse gas observation nanosatellite aiming to measure emission rates from targeted industrial sources around the world. GHGSat-D was launched into LEO on an Indian Polar Satellite Launch Vehicle on June 22, 2016 (UTC). The payload includes two instruments, the main one being a wide-angle imaging Fabry-Perot spectrometer sensing $\mathrm{CO_2}$ and $\mathrm{CH_4}$ absorption lines in the 1635-1670 nm SWIR band with a nominal spatial sampling of $23\ \mathrm{m}$ and a field of view of approximately $12 \times 12\ \mathrm{km}$, and the other one being a push-broom imaging visible-near-infrared spectrometer. The main instrument employs a novel "push-mop" sensing paradigm where a series of closely overlapping 2D images are taken, where the combined effect of the Fabry-Perot resonator and scene scrolling induces a different spectral selection of the surface in each image. In this paradigm, the processing algorithm combines image registration and a detailed forward model to retrieve spatially resolved column density arrays for $\mathrm{CO_2}$ and $\mathrm{CH_4}$. From these, dispersion modeling is used to estimate emission rates from sources within the field of view. We first describe the instrument configuration, acquisition sequence and the current retrieval algorithms. We then present real and simulated sample signals, images and retrieval results. We detail some algorithm shortcomings and how they will be addressed. We then examine some issues with the optical system and radiation damage that limit the performance of GHGSat-D and describe how they will be overcome in follow-up missions.



(a) Corrected detector output

(b) Radial signal

Figure 1: *On the left, sample corrected detector output image showing the* $\mathrm{CO_2}$ *and* $\mathrm{CH_4}$ *absorption rings. This is one of the 150 images of the sequence acquired on August 1st, 2016 over the San Juan (New Mexico, USA) region. On the right, average radial signal plot from a December 6th, 2016 observation of the Kraftwerk Niederaussem power plant (Germany). The radial average is performed over all the frames, and is expressed in units of per-pixel photocurrent in* $\mathrm{e^-/s}$.

MicroCarb mission performances (L1 & L2)

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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: CO2 at 1.61 and 2.03 µm, O2 at 0.76 and 1.27 µm. The aimed random error precision is <1ppm for a regional bias <0.1ppm. After a first talk (F. Buisson) dedicated to a status of the project and a second one (D. Pradines) to technical aspects, we here focus on mission performances and processing tools.

We will present our L1 and L2 processing tools. We detail the main hypothesis of our L2 XCO2 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 XCO2, 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 band. Compared to previous mission with similar objectives, this 1.27 µm band is an innovation enabled by our instrumental concept. This band should help to retrieve an accurate XCO2 even in aerosol loaded conditions, provided the mesospheric airglow emitting in this band can be accounted for.

Inter sensor comparison between GOSAT and OCO-2 spectral radiance and retrieved carbon dioxide

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GOSAT/TANSO-FTS and OCO-2 observe sunlight reflected from the Earth's surface and retreive atmospheric carbon dioxide (CO_2) with diffrent observing geometries and ground track repeat cycles. In this work, we compared observed radiance spectra within the three shortwave infrared (SWIR) channels shared by the TANSO-FTS and OCO-2 and retreived estimates of column averaged CO_2 dry air mole fraction at temporally coincident and spatially collocated points.

GOSAT and OCO-2 collect measurements in Nadir, Glint and Target modes. Especially in the Glint and Target modes, they measure with large, off-nadir viewing angles. For manysurface types, the effect of differences in surface bidirectional reflectance distribution function (BRDF) cannot be ignored. We corrected BRDF effects using the MODIS BRDF product, but these products have uncertainties. Therefore we picked up near-nadir observation to compare spectral radiance and CO_2 density.

Most measured spectral radiances agree within 5% for all bands shared by the two instruments. However we observed wavelength dependent differece within the O_2A band.

Retrieved CO_2 densities also agree within +/- 4ppm (1%). There is no significant correlation with aerosol optical depth (AOD), topography, and solar zenith angle. We found larger deviations for bright targets. We will show a detailed analysis using our common vicarious calibration data at Railroad Valley (RRV) in Nevada, USA and data over Australia, where data covering a wide radiance range are available.

Application of PCA to the GOSAT TIR Data for Noise Filtering and Calibration Monitoring

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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. The UW-Madison SSEC has extensive experience in the use of principal component analysis to provide noise filtering for hyperspectral infrared data (*Antonelli, et al.* 2004). Reconstruction of GOSAT TIR radiances with a reduced number of PCs produces radiance spectra with significantly lower uncorrelated noise. Since the methane region near 1306 cm^{-1} has poor signal to noise in the original TIR band spectrum, we recommend that the TIR working group apply PCA noise filtering to the GOSAT radiances prior to performing CH4 retrievals. This paper describes the use of PCA applied to GOSAT TIR for noise filtering and monitoring of the instrument calibration. Preliminary results suggest a reduction in the random instrument noise in the 1200-1400 cm^{-1} spectral region by at least a factor of ten is possible. PCA noise filtering will increase the signal to noise in this spectral region and should lead to greater sensitivity to small changes in the methane profile. Retrieval of methane from the noise filtered GOSAT TIR radiances is expected to increase the usefulness of individual footprint samples to observe regional scale gradients in the mid-troposphere. Another application of PCA is to monitor the PC scores computed from the calibrated Earth radiances over the time period of the GOSAT collection record. The time variation of selected PC scores can be used as a check on the data quality and lead to the identification of radiance spectra that are outliers and should be marked bad. Progress toward these goals and recommendations for future routine processing will be presented.

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Sentinel 5 precursor and the TROPOMI shortwave infrared total column products

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Summer 2017, the TROPOMI instrument will be launched as payload of the Sentinel-5 Precursor mission. The instrument comprises a shortwave-infrared (SWIR) spectrometer module observing Earthshine radiances around 2.3 μm. Based on these measurements, data exploitation will provide users with the global total column distribution of methane, carbon monoxide, water vapor and its isotope HDO. In this presentation, we will discuss the results of our ten years mission preparation to infer these atmospheric abundances for operational and scientific purposes. The main challenge of the processor development is to ensure the required data quality without exceeding the computational constraints of the processing facility. We discuss the algorithm baseline and the processor performance for the SWIR trace gases including an estimate of the data quality based on simulated measurements. Moreover, to demonstrate the maturity and heritage of the algorithms, we show recent applications to GOSAT and SCIAMACHY measurements and the verification with on-ground validation measurements.

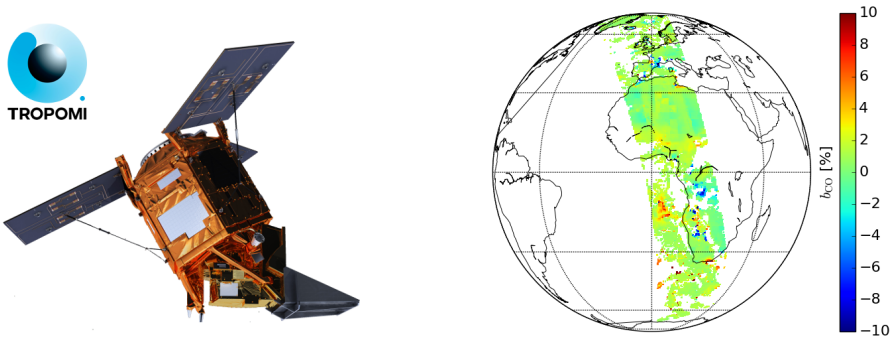

Figure 1: *left: TROPOMI on the Sentinel 5 Precusor satellite (artist impression), right: CO retrieval bias for one orbit of simulated TROPOMI SWIR measurements.*

SCIAMACHY: Spectral Calibration in the SWIR Channels

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SCIAMACHY (SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY) was a scanning nadir and limb spectrometer covering the wavelength range from 212 nm to 2386 nm in 8 channels. It doubled its originally specified in-orbit lifetime of five years before the communication to the ENVISAT platform failed in April 2012. We are now in the postprocessing phase F. The instrument was designed to measure column densities and vertical profiles of trace gas species in the mesosphere, in the stratosphere and in the troposphere. It can detect a large amount of atmospheric gases (e.g. O3, H2CO, CHOCHO, SO_2, BrO, OClO, NO_2, H2O, CO, CH_4, among others) and can provide information about aerosols and clouds.

The standard spectral calibration of the SCIAMACHY detectors is done with an on-board Spectral Line Source (SLS) by comparing theoretical line positions with line positions retrieved during calibration measurements. However, the used PtCrNe lamp does not have enough strong lines in the SWIR range (channels 6 -8) upwards of 1000 nm. The retrieval of in-flight line positions is additionally hampered by many damaged detector pixels of the SWIR detectors. An analysis of the mission data showed that for channels 6-8 no in-flight correction of the on-ground spectral calibration can be done with the standard approach, even at the beginning of the mission with a significant lower number of damaged pixels. We therefore started a study to investigate an alternative spectral calibration approach. In this approach a highly resolved reference spectrum is fitted with a DOAS like algorithm to retrieve the wavelength for each detector pixel. This approach was already tested by us for the Sentinel-4 UVN and the former Earth Explorer 8 candidate mission CarbonSat. For the method to work it is essential to have a good knowledge of the in-flight spectral response function and its change over time. Preliminary results show that the shape of the response function deviates from the current assumption of a Gaussian. For a successful fit it is also necessary to handle the many outliers caused by the bad pixels in an appropriate way. In this paper we present the first results of our investigations, focussing on channel 6 and the methane retrieval window.

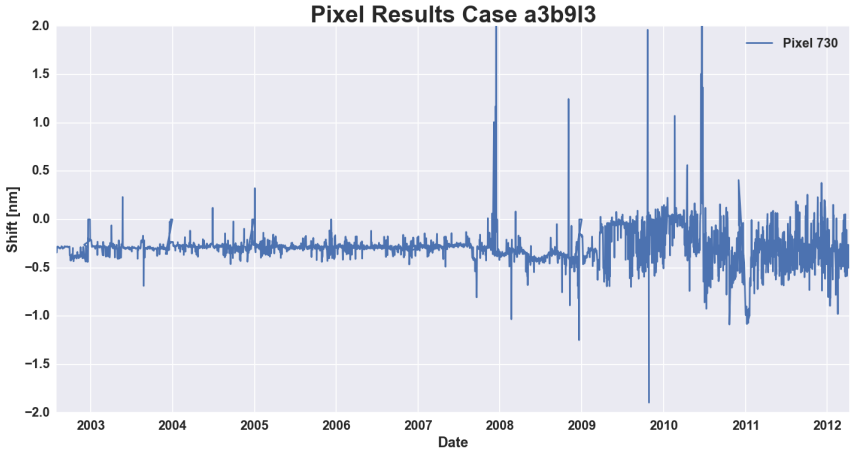

Figure 1: *First test calculation for the wavelength calibration in channel 6 (pixel 730 @ 1.53μm). The difference to the on-ground calibration is shown. Late in the mission the fit worsens, likely due to detector degradation.*

Early phase achievement of TanSat

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As the large developing and GHG emission country, China is seeking the sustainable development and trying to monitor and reduce the GHG emission. The ministry of science and technology of the people's republic of China had sponsored the Chinese carbon dioxide observation satellite (TanSat) mission 6 years ago. After successfully launched on December 22 in Jiuquan Satellite Launch Center, TanSat is going into initial experimental phase from January to April 2017, the two payloads have conducted a series of on-orbit calibrations. Preliminary assessment of TanSat CO_2 spectrometer has demonstrated satisfied performance in spectra data of O_2A band, CO_2 weak and CO_2 strong bands. More detailed experiments on the radiometric and spectral calibrations, different observation modes and retrieval testing will be projected from April to June 2017.

According to the scientific application plan of TanSat observation and the data sharing policy from Chinese government, TanSat Science team will make great efforts to promote the international cooperation on the TanSat data applications. The calibrated Level 1 data and validated Lever 2 data will be released to the international and domestic scientific researchers and common users. The TanSat observations will contribute to the CO_2 monitoring over regional and global scales and finally to support the sustainable development goals.

Recent Progress in NIES GOSAT and GOSAT-2 Projects

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Greenhouse Gases Observing Satellite (GOSAT) and its successor, GOSAT-2, are Japanese earth observing satellites for greenhouse gases (GHG) measurements from space. Both satellite projects are joint efforts among Ministry of the Environment (MOE), Japan Aerospace Exploration Agency (JAXA), and National Institute for Environmental Studies (NIES). NIES is responsible for generation, archiving, distribution, and validation of higher-level products from GOSAT and GOSAT-2.

GOSAT was launched in January 2009 and has been operated for more than eight years. It has a Fourier transform spectrometer (FTS) for the measurements of columnar abundances of carbon dioxide (CO_2) and methane and a UV-VIS-NIR-SWIR imager (CAI) for cloud and aerosol detection. Various GOSAT products and documents are currently available from GOSAT Data Archive Service (GDAS, https://data2.gosat.nies.go.jp/index_en.html). GOSAT FTS SWIR Level 2 products are columnar amount / concentration data for CO_2, methane and water vapor since April 2009. They are validated mostly using Total Carbon Column Observing Network (TCCON) data. Global CO_2 and methane flux products (GOSAT Level 4A products) are available from June 2009 to October 2013 (CO_2) and June 2009 to September 2013 (Methane). In addition, whole atmosphere monthly mean CO_2 concentration data are available from NIES GOSAT Project's website (http://www.gosat.nies.go.jp/en/recent-global-co2.html). Enhancements of CO_2 / methane column concentrations due to anthropogenic GHG emissions are estimated using GOSAT data. The estimated enhancements can be compared to those derived from GHG emission inventories. MOE and NIES are now working together to establish and spread this methodology for independent verification of national GHG inventories.

GOSAT-2 will be launched in FY2018. GOSAT-2 instruments (FTS-2 and CAI-2) are designed based on the experiences of GOSAT instruments. FTS-2 will have the extended spectral coverage for carbon monoxide measurement and the intelligent pointing capability to avoid cloud contamination. CAI-2 will have multiple UV bands for more precise land aerosol monitoring and the forward/backward viewing capability to avoid sun glint over oceans. GOSAT-2 Data Processing System (G2DPS) is a dedicated ground data system for GOSAT-2 developed at NIES. Data processing algorithms developed by scientists in NIES and GOSAT-2 Science Team are adopted for the generation of GOSAT-2 Level 2 - 4 products at G2DPS. Critical design reviews of G2DPS were completed and its manufacturing is ongoing. GOSAT-2 standard products to be generated by G2DPS include Level 2 columnar amount / concentration of CO_2, methane, and carbon monoxide from FTS-2 and Level 4 CO_2 and methane global flux products with about 10 x 10 degree grid. Validation of GOSAT-2 FTS-2 Level 2 products will be similar to that of GOSAT. To mitigate the validation data scarcity in tropical regions, a new TCCON site, Burgos, Philippines, was installed in December 2016 as one of GOSAT-2 related activities. In addition to G2DPS, a quick response system, GOSAT Air Pollution Watch, is being developed to distribute atmospheric pollution maps derived from GOSAT-2 CAI-2 data in a timely manner.

Comparison of thermal infrared measurements of CO_2 from GOSAT and IASI over the Arctic Ocean in summer

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Among the instruments performing remote sensing from space, measurements using Fourier Transform Spectrometers (FTS) operating in the thermal infrared (TIR) spectral domain are not hampered by the requirement of not too high solar zenith angles as in SWIR measurements.

In this study, we compare retrievals of several geophysical parameters performed from IASI (L1C) and TANSO-FTS (L1b) spectra recorded in the TIR domain. We will use the latest GOSAT version (v203203) of the corresponding spectra. Due to the orbits of the MetOp and GOSAT satellites, good coincidences can be found in the polar areas. We will consider spectra acquired in the summer (to select spectra SNR not too low), in the 68N-82N latitude range. Since the spectral sampling and weighting functions are different for these two instruments, the comparison is done on retrieved parameters (SST, XCO_2) rather than on the spectra themselves. Statistics of pairwise differences between sounder footprints will be presented as a function of the spatial distance between the IFOV centers and of the time lag between measurements.

Overview of MicroCarb operations concepts

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MicroCarb is a European initiative for the monitoring of CO2 fluxes and a better understanding of the mechanisms that control these fluxes. It will provide atmospheric CO2 concentrations data to the scientific community, in the continuation or in parallel to the on-going operational programs (GoSat, OCO, Tansat).
The MicroCarb instrument is a grating spectrometer that acquires high-resolution spectra in 4 bands between 0.76µ and 2.1 µm. It will fly on board a micro satellite with a mass lower than 200 kg with performances in line with the standards for CO2 measurements (i.e. 1ppm accuracy). Together with the requirement for a cost effective development, the compactness is made possible by an innovative optical design. Compared to previous mission with similar objectives, a specific innovation is the use of an additional spectral band at 1.27 µm (O2 absorption) that may allow a better normalization of the CO2 column, provided the airglow can be accounted for.
The project is conducted by the CNES in partnership with the UK Space Agency, and involves the scientific community from both France and UK.
MicroCarb project has now completed its preliminary design phase (phase B), is firmly decided, and is starting the realization phase.

After a first presentation (Author: F. Buisson) giving a progress status of the project, this one will focus on technical features: choice of the possible orbits, fields of view geometry and sampling, geometrical performances, acquisition modes and mission plan optimization (according to lands/oceans mask, but also possibly to meteorological forecasts…), calibration strategy…
A poster (Author: D. Jouglet) will be dedicated to mission performances expected with MicroCarb updated concept.

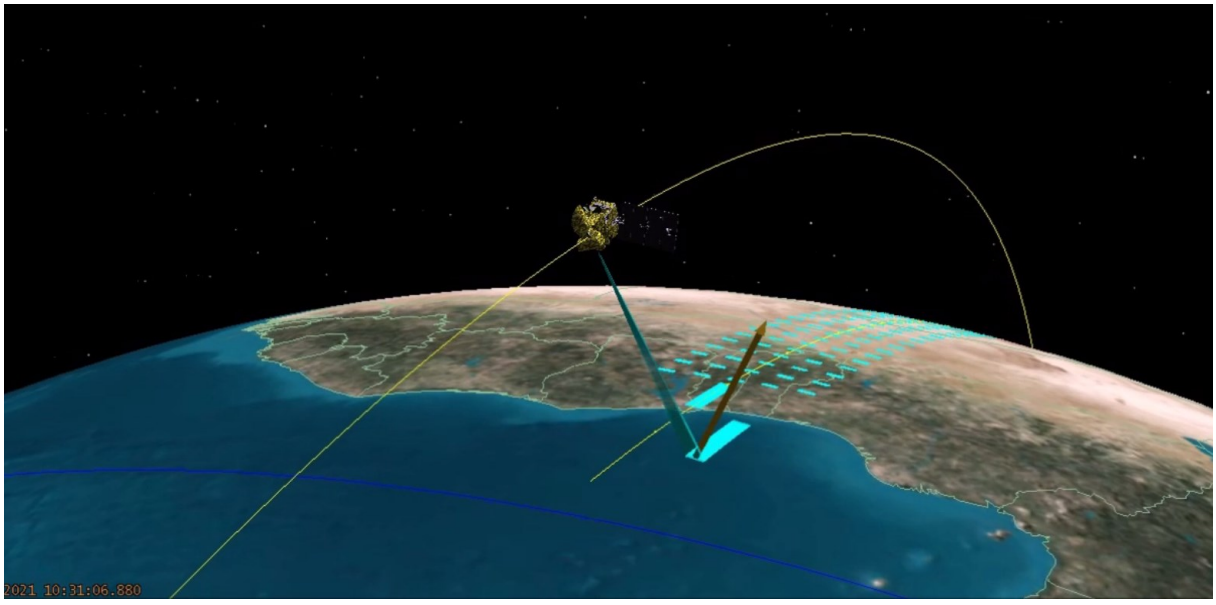

Figure 1: *example of Scan, Nadir, then Glint acquisition modes sequence*

Prelaunch Spectral Calibration of the TanSat's Atmospheric Carbon Dioxide Grating Spectroradiometer

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TanSat is a key satellite mission of China Earth Observation programme, which is designed to measure global atmospheric column-averaged CO_2 dry air mole fraction (XCO_2) using one spectroradiometer of visible and near infrared solar reflected spectrum.

This paper describes the prelaunch spectral calibration of the Atmospheric Carbon dioxide Grating Spectroradiometer (ACGS) on the TanSat. Several critical aspects of the ACGS such as the spectral resolution, the spectral dispersion and the Instrument Line Shape (ILS) function of each channel directly related to produce the Level 1 products were evaluated. The determination of these spectral parameters was conducted through a tunable diode-laser and wavemeter combining experiment.

The results showed that ACGS ILSs were noticeably symmetric and perfectly consistent across all channels in three bands; the variations of ILS resulted in errors of radiometric response and spectral calibrations were negligible. The spectral resolution characteristic met the requirement. The spectral dispersion was excellent consistency in spatial dimension of each band, and was good linearity in spectral dimension of each band. Taken together, these results suggest that the ACGS spectral characteristics have met the mission requirement.

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Preliminary Assessment of TanSat Atmospheric Carbon Dioxide Grating Spectroradiometer on-orbit Performance

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The successful launch of the Chinese key Earth Observation satellite TanSat on 22 December 2016 with the main instrument Atmospheric Carbon Dioxide Grating Spectroradiometer (ACGS) signifies a new step of satellite atmospheric CO2 measurement capabilities following the legacy of SCIMACHY, GOSAT and OCO-2. TanSat, as the third satellite mission dedicated to measure atmospheric CO2 from space, has an opportunity to learn some lessons from GOSAT and OCO-2 missions; it was designed to measure global atmospheric CO2 concentrations monthly using satellite in Sun-synchronous near-polar orbit. The ACGS consisted of three spectral bands: the oxygen absorbing A-band with centroid wavelength of 760nm; weak and strong carbon dioxide absorbing band centroid wavelength are 1610nm and 2060nm, which are used to measure atmospheric CO2. Its spatial resolution is 2 x 2 km, swath was ~20 km, mass is 204 kg, and peak power is 255 W. The NSMC/CMA are in charge of data acquisition, processing and dissemination of TanSat. After the power on of ACGS on 9 January 2017, the team of TanSat ground segment begun to on-orbit check out. This paper reported preliminary assessment results of ACGS on board spectral and radiometric characterization; spectral resolution characterization met the requirement through the comparison with solar Fraunhofer lines. The index map of bad pixels was rechecked on board; The mode of dark current response with temperature for two CO2 bands was been rebuilt using all orbit dark current observation. The gain coefficients mode of three bands had a good stability and been used retrieval application.

2 Retrieval Algorithms and Uncertainty Quantification

Latest developments of the University of Leicester XCO_2 and XCH_4 retrieval algorithms for GOSAT: Support for ESA's GHG-CCI and Copernicus C3S programmes

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More than 7 years of global observations of the atmospheric distribution of CO_2 and CH_4 are now available from GOSAT. These datasets, once combined with models of atmospheric transport, provide a unique resource for constraining regional CO_2 and CH_4 surface fluxes and to test land surface model calculations.

At University of Leicester (UoL), we have developed a 'full-physics' retrieval algorithm for the retrieval of XCO_2 and XCH_4 from GOSAT NIR/SWIR spectra based on the Optimal Estimation method. One key feature of the algorithm is that the a priori information for aerosols is constrained with data from the ECMWF MACC (now CAMS) aerosol model. We also utilize the proxy method retrieval method which is based on the retrieved XCH_4/XCO_2 ratio.

The full physics and the proxy retrieval of UoL allow for the generation of stable long-term datasets of global CO_2 and CH_4 columns, in line with the Global Climate Observing System (GCOS) requirements for Essential Climate Variables (ECV) from satellite-derived products. UoL has contributed GOSAT-derived XCH_4 and XCO_2 spanning 2003-2015 to the ESA GreenHouse Gas Climate Change Initiative (GHG-CCI) which is now continued up to 2017 as part of the Copernicus Climate Change Service (C3S) program. These datasets have recently been used in comparisons with chemical transport models and in quantifying emissions from biomass burning (e.g. Lindqvist et al, 2015; Parker et al, 2015, 2016)

In this presentation, we will summarize the recent retrieval algorithm developments at UoL and give an overview over the validation and model comparisons using the GOSAT datasets.

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Uncertainty quantification for OCO-2 remote sensing retrievals via Monte Carlo simulation

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We present a general framework for uncertainty quantification of remote sensing retrievals, and show how it is used to quantify uncertainties in OCO-2's retrievals of XCO2. The OCO-2 retrieval algorithm is based on the optimal estimation method of *Rodgers* (2000). It provides estimates of the first two moments of the posterior distribution of XCO2 for each sounding, denoted by $\hat{X}$ and $\hat{S}$, respectively. Numerous factors, including computational approximations and not-fully-known auxillary inputs, cause these computed values not to be equal to the corresponding *true* posterior moments, $\mu_{\text{XCO2}|\mathbf{Y}}$ and $\sigma^2_{\text{XCO2}|\mathbf{Y}}$, where the subscript XCO2$|\mathbf{Y}$ indicates conditioning on the observed radiance vector, $\mathbf{Y}$. We argue that uncertainty quantification in this context is the quantification of the statistical properties of $\hat{X}$ and $\hat{S}$ as estimates of $\mu_{\text{XCO2}|\mathbf{Y}}$ and $\sigma^2_{\text{XCO2}|\mathbf{Y}}$, respectively.

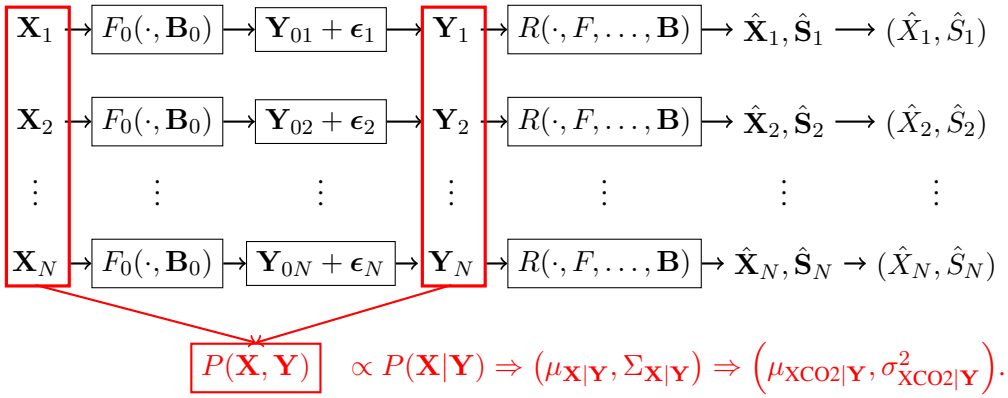

Figure 1: *Simulation framework for assessing the statistical properties of OCO-2's retrieved XCO2 posterior mean and variance.*

We do this by simulating the joint distribution of the true state vector, $\mathbf{X}$, its corresponding radiance, $\mathbf{Y}$ (using a realistic forward function denoted F_0 with parameters $\mathbf{B}_0$), and the OCO-2 retrieval algorithm's estimate, $(\hat{X}, \hat{S})$ as shown in Fig. 1. The simulated tuples are $\{\mathbf{X}_n, \mathbf{Y}_n, \hat{X}_n, \hat{S}_n\}_{n=1}^N$, where N is the number of trials in the simulation. The set $\{\mathbf{X}_n, \mathbf{Y}_n\}_{n=1}^N$ is used to model the true (multivariate) posterior moments, $\boldsymbol{\mu}_{\mathbf{X}|\mathbf{Y}}$ and $\boldsymbol{\Sigma}_{\mathbf{X}|\mathbf{Y}}$, using a Gaussian mixture model. These are converted to corresponding total column quantities, $\mu_{\text{XCO2}|\mathbf{Y}}$ and $\sigma^2_{\text{XCO2}|\mathbf{Y}}$, respectively. The bias and variance of the ensemble of $\hat{X}$ values is assessed relative to $\mu_{\text{XCO2}|\mathbf{Y}}$, and likewise for $\hat{S}$ relative to $\sigma^2_{\text{XCO2}|\mathbf{Y}}$.

In this talk, we discuss the strengths and weaknesses of our approach, and provide results obtained for OCO-2 ocean glint retrievals over a selected area of the Pacific Ocean in July 2015.

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EOF-based XCO_2/XCH_4 retrieval algorithm: Towards global GOSAT data processing

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We present further development of the EOF (Empirical Orthogonal Functions)-based XCO_2 retrieval algorithm, *Bril et al.* (2017) for the GOSAT data processing. This algorithm performs EOF-based decomposition of the measured spectral radiance and derives the relationship of limited number of the decomposition coefficients with target gas amount and a priori data. These regression relationships were derived using training sets of collocated GOSAT and ground-based observations.

The algorithm was applied for global XCO_2 and XCH_4 retrievals from GOSAT observations from June 2009 to May 2014. All over-land observations that pass Cloud and Aerosol Imager filtering were processed (totally about 700,000 observations). Several retrieval sets were computed using different training procedures. The results were compared with collocated TCCON observations as well as with retrieval results of other algorithms, including ACOS (version B3.5), RemoteC (v. 2 .35) and NIES (v. 02.21).

Training sets of the collocated GOSAT-TCCON observations include as a rule multiple GOSAT data for each TCCON XCO_2 value (which is the average over time within +/- 1 hour of GOSAT overpass). Such training procedure apparently imposes implicit averaging over these multiple collocations. This assumption is supported by the good agreement of EOF-based XCO_2 estimates with ACOS XCO_2 retrievals that were additionally averaged over the 5°-latitude-longitude circle around the location of the observation (similar area is used for the selection of GOSAT-TCCON collocations). Besides, EOF-based XCO_2 are in good agreement with TCCON collocations not used for the training.

Other algorithm option used for the training the small subset (~5%) of the XCO_2 retrievals obtained by RemoteC full-physics algorithm. For this option we found large XCO_2 retrieval errors for the GOSAT-TCCON collocations that were strongly affected by atmospheric light scattering. It apparently follows from the fact that such ”affected observations” are mostly filtered out from the training data set, and the derived EOF-based regressions were not trained to correct for optical path modification due to light scattering. Additional filtering is required for trhis algorithm option and it was implemented by the comparison of the EOF-estimates of surface pressure with corresponding meteorological data. After the filtering EOF-based XCO_2 retrievals were shown to be in a good agreement with other algorithm results as well as with collocated TCCON data.

Similar EOF-based algorithm for XCH_4 retrievals was implemented and tested using GOSAT radiance spectra in 1.67 μm CH_4 absorption band.

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Overview and latest results of ESA's GHG-CCI project and Copernicus Climate Change Service (C3S) operational continuation

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and the GHG-CCI *) and C3S_312a_Lot6 #) project teams

The GHG-CCI project (http://www.esa-ghg-cci.org/) is one of several projects of the European Space Agency's (ESA) Climate Change Initiative (CCI) (*Hollmann et al., 2013*). The goal of the CCI is to generate and deliver data sets of various satellite-derived Essential Climate Variables (ECVs) in line with GCOS (Global Climate Observing System) requirements. The "ECV Greenhouse Gases" (ECV GHG) is the global distribution of important climate relevant gases – specifically atmospheric CO_2 and CH_4 - with a quality sufficient to obtain information on regional CO_2 and CH_4 sources and sinks. The focus of GHG-CCI is to generate long-term highly accurate and precise time series of global CO_2 and CH_4 column-averaged dry-air mole fraction data products, i.e., XCO_2 and XCH_4, obtained from SCIAMACHY/ENVISAT and TANSO-FTS/GOSAT. An overview about the project and its achievements will be presented focusing on the latest data set and its quality (*Buchwitz et al., 2017*). The GHG-CCI data sets will be extended in the future within the framework of the Copernicus Climate Change Service (C3S).

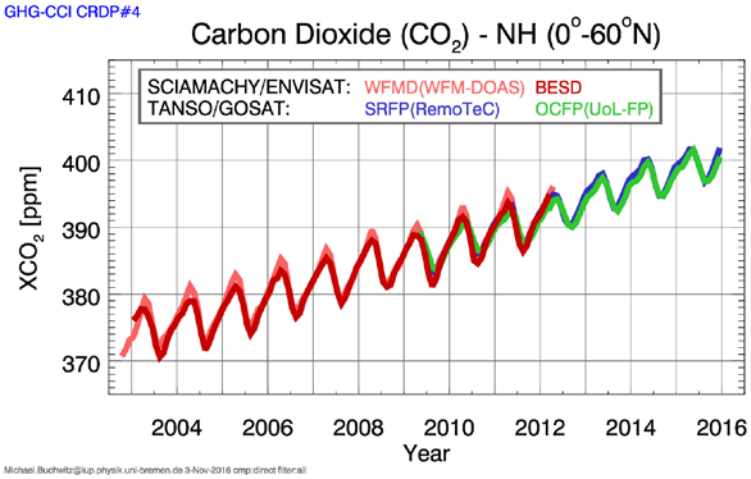

Figure 1: *Time series of Northern hemispheric XCO_2 as obtained from two SCIAMACHY/ENVISAT and two TANSO-FTS/GOSAT GHG-CCI XCO_2 retrieval algorihms.*

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*) M. Reuter, O. Schneising, H. Boesch, I. Aben, P. Bergamaschi, H. Bovensmann, D. Brunner, B. Buchmann, J. P. Burrows, A. Butz, F. Chevallier, C. D. Crevoisier, R. G. Detmers, B. Dils, L. Feng, C. Frankenberg, O. P. Hasekamp, W. Hewson, J. Heymann, S. Houweling, S., T. Kaminski, A. Laeng, G. Lichtenberg, J. Marshall, M. De Mazière, S. Noël, J. Notholt, P. Palmer, S. Pandey, R. Parker, M. Scholze, P. Somkuti, G. P. Stiller, A.-M. Sundström, E. De Wachter, T. Warneke, and C. Zehner

#) M. Reuter, O. Schneising, H. Boesch, I. Aben, J. Anand, R. Armante, C. D. Crevoisier, R. G. Detmers, O. P. Hasekamp

Analysis of aerosol information content in CAPI/TanSat observation over land and induced error in CO_2 retrieval from aerosol

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Abstract: 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 CO_2 measurements. This study aims to assess the information content about aerosol properties that can be obtained from CAPI's observations as well as the interference error in hyperspectral CO_2 retrieval from aerosol. We simulate synthetic CAPI observations using the UNified Linearized Vector Radiative Transfer Model (UNL-VRTM), from which the degree of freedom for signal (DFS) and a posteriori error for various state vector parameters are calculated using optimal estimation theory. The simulation considers different combinations of fine and coarse aerosols and BRDF for both soil and vegetation surfaces. It is found that CAPI can provide 3 to 4.5 independent pieces of information about aerosol parameters, mainly focusing on related to aerosol total volume (or aerosol optical depth), the fine mode fraction (fmf_v) of aerosol volume, and imaginary part of refractive index for coarse mode aerosols. At directions around back-scattering, aerosol information content is smaller due in part to the large directional surface reflectance. Due to weaker scattering of coarse aerosol, the information content of large particle is relatively less. As fmf_v decreases, DFS remains large for fine aerosol and increases for coarse aerosol. With larger aerosol optical depth (AOD), more aerosol information content can be obtained, but when AOD increases to a threshold ranging from 0.5 to 1.2, aerosol DFS doesn't increase any more. Furthermore, the degree of linear polarization (DOLP) is shown to be more sensitive to aerosol properties than reflectance, hence improves CAPI's aerosol retrieval accuracy. The additional information content raised from DOLP measurements ranges from 1 to 1.8 in terms of DFS and reaches the largest in conditions of $0.2 < fmf_v < 0.4$ at SZA < 60°. If AOD is known as a priori (for example, from other A-Train satellites), total DFS for aerosol information content can be improved by 0.8 to 1.6 in most cases, and could exceed 2.0 for conditions of small AOD (< 0.2). However, the improvement has little dependence on AOD if AOD is larger than 0.2. At the end, the interference error in XCO_2 due to aerosol properties is less than 0.1 ppm over soil, but can pass 0.2 over vegetation. The uncertainty of aerosol refractive index causes larger error in XCO_2 compared with other parameters. For larger AOD, the differences of interference error between different fmf_v are larger. The interference error due to aerosol volume reaches the largest over soil when fine particles have large fraction at large AOD, but not the same over vegetation, which proves the significate impact of surface type on CO_2 retrieval error from aerosol.

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AIRWAVE: an algorithm for the retrieval of the total column of water from the measurements of the ATSR series and Sentinel 3/SLSTR

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The Advanced Infra-Red WAter Vapour Estimator (AIRWAVE) algorithm has been developed by Casadio et al. (2016) and applied to the measurements of the Along Track Scanning Radiometer (ATSR) missions for the retrieval of the Total Column of Water Vapour (TCWV). It produced a 20-year day-night TCWV dataset over sea in clear sky conditions. The quality of the obtained dataset has been evaluated against independent products derived from space borne sensors (SSM/I, MWR), from ground based remote sensing (GPS, sun-photometers), from WMO sondes (ARSA and IGRA databases) and from NWP (ECMWF ERA-Interim). The comparisons showed a general good agreement.
The algorithm, that is independent from external constrains, makes use of a set of tabulated parameters calculated off-line using a Radiative Transfer Model (RTM) specifically developed to simulate the ATSR radiances. The approach exploits the clear sky Brightness Temperature measured over the sea in forward and nadir directions in the TIR channels.
The AIRWAVE algorithm has been recently extended to the Sea and Land Surface Temperature Radiometer (SLSTR) instrument, on board the European Copernicus Sentinel 3. SLSTR has the same dual view capability and TIR spectral channels of the ATSR instruments and therefore it is possible to use a similar approach for the TCWV retrieval. With respect to its precursors, SLSTR has different nadir and oblique viewing angles, a larger swath (more across track measurements) and different spectral response functions in the two TIR channels.
We will show some examples of the application of the AIRWAVE algorithm to the ATSR series and to the SLSTR measurements, evaluating the performances with comparisons against other sensors (e.g. SSM/I or MWR).

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Highlights of the HITRAN2016 database

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The HITRAN2016 database *Gordon et al.* (2017) will be released before this meeting. It is a titanic effort of world-wide collaboration between experimentalists, theoreticians and atmospheric scientists, who measure, calculate and validate the HITRAN data.
The line-by-line lists for almost all of the HITRAN molecules were updated in comparison with the previous compilation HITRAN2012 *Rothman et al.* (2013) that has been in use, along with some intermediate updates, since 2012. The extent of the updates ranges from updating a few lines of certain molecules to complete replacements of the lists and introduction of additional isotopologues. Many more vibrational bands were added to the database, extending the spectral coverage and completeness of the datasets. The amount of parameters has also been significantly increased, now incorporating, for instance, non-Voigt line profiles *Wcisło et al.* (2016); broadening by gases other than air and "self" *Wilzewski et al.* (2016); and other phenomena, including line mixing.
In addition, the amount of compounds represented in cross-sectional part of the database has increased dramatically (from ~50 to ~300) and includes many recent experiments as well as adaptation of the existing experimental databases that were not in HITRAN previously (for instance adaptation of the PNNL database *Sharpe et al.* (2004)). The new vast array of IR cross-sections allows users easy access to many categories of absorbers covering many fields of research.
The HITRAN2016 edition takes full advantage of the new structure and interface available at www.hitran.org *Hill et al.* (2016) and the HITRAN Application Programming Interface *Kochanov et al.* (2016).
This talk will provide a summary of the updates, emphasizing details of some of the most important or dramatic improvements in the spectroscopy of major greenhouse gases, including water vapor, CO_2 and methane.
This work is supported by the NASA PATM (NNX13AI59G), PDART (NNX16AG51G) and AURA (NNX14AI55G) programs.

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Accelerated aerosol retrieval algorithm MWPM-EXAM for GOSAT/TANSO-CAI and GOSAT-2/TANSO-CAI-2

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Aerosol in the atmosphere is an important constituent for determining the earth's radiation budget, so the accurate aerosol retrievals from satellite is useful. 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 wavelegths and surface reflectances. Thus, the method is useful for aerosol retrieval over spatially heterogeneous surface like an urban region.

We apply an optimal method and spatial smoothness constraint for aerosol properties, and directly combining with the radiation transfer model (RTM), Rstar (Nakajima and Tanaka, 1986, 1988). More accurate and flexible retrievals can be expected by direct use of RTM. However, it has also weak point that it takes a large computation time compared to that with LUT method.

To accelerate the calculation time, we replace the RTM with an accelerated RTM solver learned by neural network-based method (Takenaka et al., 2011), EXAM, using Rater code. We apply MWPM combined with EXAM to GOSAT/TANSO-CAI (Cloud and Aerosol Imager). CAI is a supplement sensor of TANSO-FTS, dedicated to measure cloud and aerosol properties. CAI has four bands, 380, 674, 870 and 1600 nm, and observes in 500 meters resolution for band1, band2 and band3, and 1 km for band4.

The retrieved parameters are fine and coarse mode AOTs, soot volume fraction in fine mode aerosols and surface reflectance at each wavelength by combining a minimum reflectance method and Fukuda et al. (2013). As a result, the calculation time was shortened from about 10 second to 0.01 second per pixel. And also, the similar retrieval results are obtained compared with MWPM with RTM over Beijing region.

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Study of IASI nitrous oxide (N_2O) retrievals: application to long-range transport during the Asian summer monsoon

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We use the Levenberg-Marquardt optimal estimation theory to retrieve N_2O in two different spectral regions: one located between 1250 and 1310 cm^{-1} (called hereafter B1) and another located between 2190 and 2210 cm^{-1} (called hereafter B2). We validate the retrievals using the in-situ aircraft measurements from the HIAPER Pole-to-Pole Observations. N_2O absorption band B2 is more intense than the absorption band B1 but the signal to noise ratio over B1 is better than over B2. However, B1 has also relatively intense absorption bands of methane (CH_4) and water vapor (H_2O) which interfer in the detection of N_2O in this band. We show that the IASI products are sensitive to upper tropospheric N_2O at ~300 hPa in the two bands. Using IASI upper tropospheric N_2O and HIPPO coincident measurements, we calculated a standard deviation error of about 1% both in B1 and B2. The correlation coefficients are about 0.5 and 0.6 in B1 and B2, respectively. However, due to the interference of CH_4 and H_2O in B1, we discard much more retrievals in B1 than in B2. We also compare the IASI N_2O retrievals and the results from the Atmospheric Chemistry Transport Model (ACTM) by focusing on the long-range transport of N_2O between Asia and Europe. In agreement with the model outputs, we showed that the retrievals in B2 capture N_2O long-range transport features with a temporal scale of about 2-3 days (Fig. 1) whereas the retrievals in B1 can only capture monthly variations . IASI N_2O retrievals in B2 can therefore be a useful product to study, with a 2-3 days resolution, the transport of N_2O via the Asian monsoon anticyclone (see *Kangah et al.*, 2017).

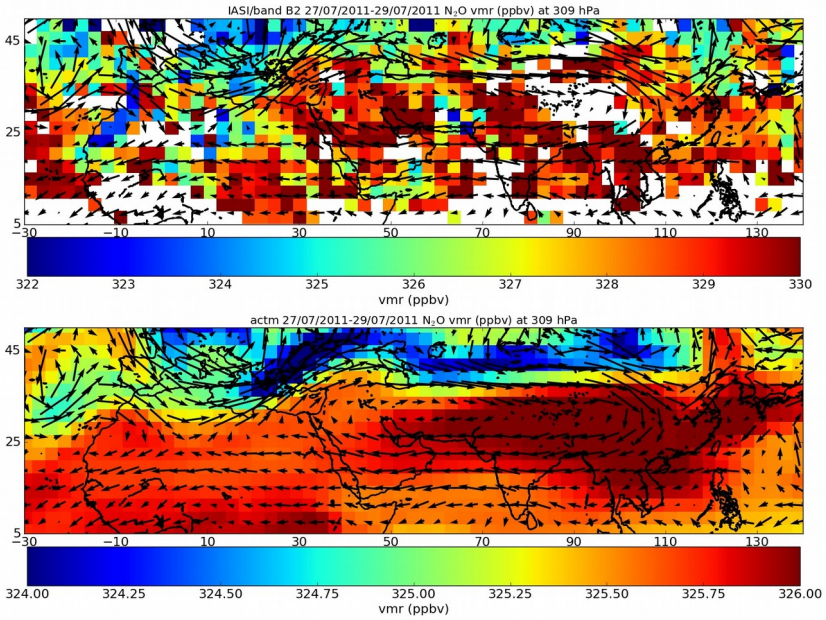

Figure 1: *Distribution of N_2O at 309 hPa from 27 to 29 July 2011 observed by IASI B2 (top) and calculated by the ACTM model (bottom).*

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Validation of OCO-2 and ACOS-GOSAT using HIPPO and TCCON

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Consistent validation of satellite CO_2 estimates is a prerequisite for using multiple satellite CO_2 measurements for joint flux inversion and establishing a long-term atmospheric CO_2 data record. We validate recent satellite observation of OCO-2 v7 and ACOS-GOSAT v7.3 using similar analysis as previous work through comparisons to the HIAPER Pole-to-Pole Observations (HIPPO) and the Total Carbon Column Observing Network (TCCON) to estimate biases and errors affecting carbon cycle science. CarbonTracker RT is also compared to the validation data, and additionally used to evaluate the mismatch between the HIPPO observation timeframe and the OCO-2 record, which are offset by 3-7 years. Some key metrics that are validated include the seasonal cycle phase and amplitude, latitudinal gradient by season, regional biases, and errors with respect to averaging.

Dimension reduction methods for remote sensing of methane profile

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In atmospheric remote sensing, determining the density profiles of trace gases from measured absorption spectra is an ill-posed inverse problem, in which the measurement typically contains limited amount of information. In this work, we consider ground based Fourier transform infrared spectrometer (FTIR, part of TCCON network [1]) solar absorption measurements from Sodankylä station, located at Northern Finland, to invert trace gas density profiles ranging from 0 to 40 km. We use Bayesian framework with optimization and adaptive MCMC to characterize the full posterior distribution of the solution and the related uncertainties. Using prior reduction from [2] and likelihood-informed subspace (LIS) dimension reduction approach described in [3], we identify the the low dimensional subspace of the parameter space that contains most of the measurement's information, and implement computational methods to solve the inverse problem in determination of atmospheric methane (CH4) density profiles. We validiate the results of inversions by comparing them against direct measurements from co-located AirCore Atmospheric Sampling System balloon experiments, described in [4].

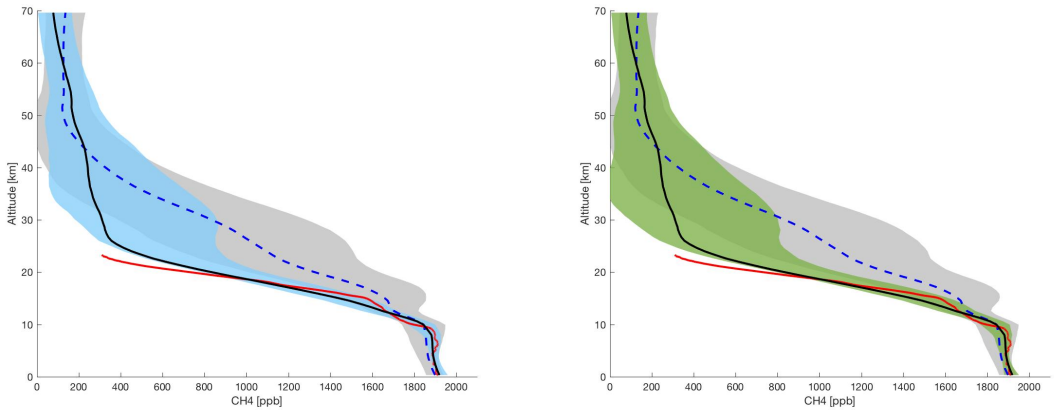

Figure 1: Solutions for posterior distribution, prior shown in grey, AirCore in red. Left: full space (dimension: 51), right: LIS (dimension: 3).

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Improved Orbiting Carbon Observatory-2 (OCO-2) Retrievals Using a BRDF Model for the Surface

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The Orbiting Carbon Observatory-2 (OCO-2) is NASA's first dedicated Earth remote sensing satellite to study atmospheric carbon dioxide from space, and was launched successfully on July 2, 2014. Retrievals in the target mode (where the Observatory locks its view onto a specific surface location, and scans back and forth over that target while flying overhead) show biases that appear to be due to not accounting for bidirectional surface reflection (BRDF) effects, i.e., the non-isotropic nature of surface reflection (see Figure 1). To address this issue, we implement a realistic BRDF model. The column averaged CO_2 dry air mole fraction (XCO_2) results using this new model show much less variation with scattering angle (or airmass). Further, the retrieved aerosol optical depth (AOD) is in much better agreement with coincident AERONET values. We also show results using the BRDF model on land nadir and glint measurements, measurements over Total Carbon Column Observing Network (TCCON) sites and over selected small areas.

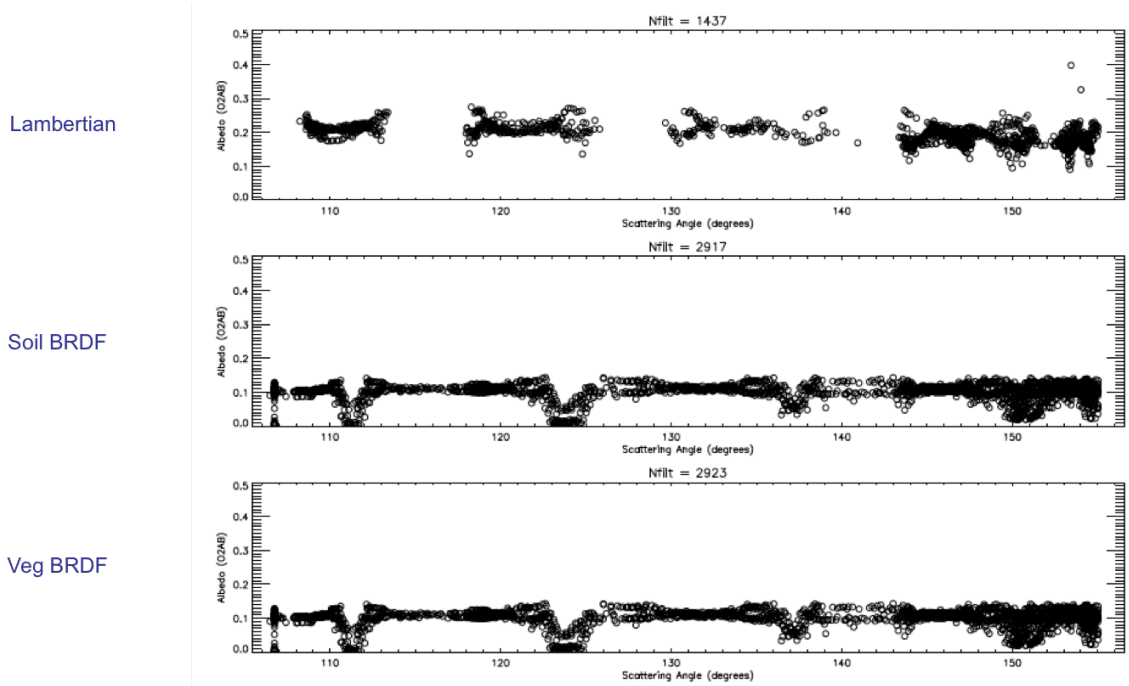

Figure 1: *Retrieved albedo using (top) Lambertian model and (middle, bottom) BRDF models. The Lambertian model produces an unphysical slope as a function of scattering angle.*

Using GEOS-5 Aerosols to Inform the OCO-2 CO_2 Retrieval

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The primary goal of OCO-2 is to use hyperspectral measurements of reflected near-infrared sunlight to retrieve column-mean carbon dioxide with the accuracy and precision needed to improve our estimates regional carbon fluxes. These accuracy requirements can only be met, however, if the light-path modification effects of clouds and aerosols are taken into account. The current OCO-2 aerosol parameterization is simplistic and the corresponding retrieved aerosol information compares poorly to AERONET (*Nelson et al.*, 2016). In this work, we create a more complex aerosol parameterization to better inform the CO_2 retrieval algorithm. Specifically, we evaluate the impact of 3D aerosol fields from the Goddard Earth Observing System Model, Version 5 (GEOS-5) on the retrieved column-mean CO_2 from OCO-2. By fitting a Gaussian profile to the GEOS-5 aerosol profiles and ingesting them with low uncertainty into retrieval algorithm we hope to better constrain the retrieval and reduce errors in X_{CO2}. Here, we present results of a comparison between the retrieved X_{CO2} measurements and TCCON. Future studies include modifying the OCO-2 retrieval algorithm to be able to ingest full GEOS-5 vertical profiles of aerosol as well as addressing the bias by incorporating a stratospheric aerosol component from temporally and spatially averaged CALIPSO measurements.

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Recent improvements in X_{CO2} measurements from the Orbiting Carbon Observatory-2

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The Orbiting Carbon Observatory-2 (OCO-2) was launched in July 2014, with the overarching goal of measuring the column-mean dry air mole fraction of carbon dioxide (X_{CO2}) with the necessary precision and accuracy to deduce the surface-atmosphere exchange of CO_2 on regional scales (*Crisp et al., 2008)*. This formidable task requires, above all, measurements with high-accuracy because even small biases X_{CO2} product (0.25% or 1 ppm) can introduce corresponding biases in the inferred carbon fluxes (*Chevallier et al., 2014)*. The first operational version of OCO-2 X_{CO2}, called version 7 (v7), exhibited reasonably good accuracy characteristics overall, but also included apparent biases (*Eldering et al., 2017; Wunch et al., 2017)*. These biases were sometimes larger than 1 ppm in areas such as in the tropical and high latitude oceans, high northern latitude lands, near broken cloud fields, and in some areas of significant topographic variation.

In this talk, we describe these biases and the steps taken to mitigate them in the latest version 8 (v8) OCO-2 product. The most significant changes resulted from the inclusion of an optically thin ($\tau <$ 0.01) sulfate aerosol layer in the upper atmosphere of our retrieval algorithm's state vector. This "stratospheric aerosol" layer mitigates biases both due to real upper atmospheric aerosols, including those from volcanic eruptions, and lofting of fossil fuel and biomass burning products. It also highlights the impact of scattered light from ice build-up on our 0.76 μm detector, for which a correction is currently being explored as part of our instrument calibration process. The overall bias has been reduced further by updates to the gas absorption coefficients. Other changes in the v8 product include the introduction of a non-Lambertian surface bi-directional reflection distribution function (BRDF) over land, revised CO_2 and cirrus cloud priors, revised meteorological prior and additional improvements in the instrument calibration. We present the validation of this new X_{CO2} product against the ground-based TCCON network, show how the overall performance has changed relative to the previous v7 product, and discuss prospects for future improvements.

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Spectroscopy for remote sensing of greenhouse gases: Recent advances and outstanding issues

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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 work on spectroscopy for the 0.76 μm O_2 A-band and the 1.61 and 2.06 μm CO_2 bands utilized by the NASA Orbiting Carbon Observatory (OCO-2) mission, evaluate the impact of spectroscopic updates on OCO-2 retrievals 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 latest v5.0 OCO-2 ABSCO tables include results from (1) a new multispectrum analysis of O_2 spectra acquired over a wide range of temperature and pressure, where details of the line-shape profile, the extent of line-mixing and the collision-induced absorption were determined in a self-consistent model and (2) updated multispectrum analyses of the 1.61 and 2.06 μm CO_2 bands with improved constraints on the temperature dependence for these bands. These latest multispectrum analyses in all three bands are based on a speed dependent Voigt line shape with line mixing. We present results of validation of these spectroscopic updates for the OCO-2 bands using ground-based atmospheric spectra and retrievals from the Total Carbon Column Observing Network (TCCON) site in Lamont, Oklahoma. For the 1.61 and 2.06 μm CO_2 bands, we present a comparison of results from our ABSCO v5.0 model, available for the OCO-2 spectral regions only, with that of the Lamouroux et al. (2015) model that is available for CO_2 bands throughout the thermal and near infrared. We also present evaluation of ABSCO v5.0 using satellite-based spectra and retrievals. In addition to showing the reduction in residuals and retrieval biases associated with the updates, we will discuss outstanding issues and potential paths to resolving these, such as new laboratory measurements and analyses and/or incorporating line shape parameterizations that can potentially offer greater accuracy than the speed dependent Voigt.

CO_2 Sounder Multiwavelength Lidar Measurements: Retrievals, Spectroscopy, Biases and Vertical Information

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NASA Goddard's CO_2 Sounder lidar measures the column CO_2 mixing ratio by using a pulsed integrated path differential absorption (IPDA) approach. Compared to passive CO_2 spectrometers, such as those aboard GOSAT and OCO-2 satellites, pulsed lidar measurements offer many advantages. These include high-latitude and night coverage, a consistent nadir-zenith measurement geometry, robustness against aerosol and cloud contamination, precise measurement of scattering surface elevation, and partial column measurements to cloud tops.

The CO_2 Sounder instrument also employs a multi-wavelength sampling approach. It also offers unique capabilities to identify and mitigate potential biases from several sources. These include errors from small wavelength changes in the instrument as well as spectroscopic modeling of the CO_2 absorption. Precise spectroscopic modeling of a CO_2 absorption line requires adjustments for line-mixing and speed dependence, which vary depending on the spectroscopic model used. We have compared several spectroscopic models against line shape samples from CO_2 Sounder airborne data. The results find differences that can affect the X_{CO2} column retrieval by up to 2%. In addition, the results show that the multi-wavelength line sampling approach, is less sensitive to the exact line shape, compared to a two-wavelength approach.

Our CO_2 Sounder retrievals, in contrast to the traditional optimal estimation method, uses a least-squares fitting approach and an uninformative prior combined with a reduced dimensional retrieval basis to regularize the problem. The use of the uninformative prior eliminates another source of potential biases, those arising from incorrect assumptions of the *a priori* CO_2 distribution.

The multi-wavelength approach combined with the lidar's high spectral resolution also provides some vertically-resolved CO_2 information by utilizing the the altitude-dependent pressure-broadening. We have used a singular-value decomposition to obtain the principal components, that allows the retrieval to obtain information about the vertical distribution of CO_2. We will discuss this method and other alternative retrieval approaches.

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Assessment of a physically-based simultaneous retrieval for CO_2, CH_4 and N_2O from IASI observations and inter-comparison with *in situ* observations and AIRS, GOSAT, OCO-2 satellite products.

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Recent advances in the random projection approach applied to the inversion of the full IASI (Infrared Atmospheric Sounder Interferometer) spectrum are exemplified with applications to the retrieval of greenhouse gases and pollutants. The case of simultaneous retrieval of CO_2, CH_4 and N_2O is exemplified in this study. 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. Many of the methodological aspects above have been shown in a recent paper by the authors (*Serio et al.* 2016) in dealing with the retrieval of surface parameters and atmospheric temperature, water vapour and ozone profiles. The present analysis is aiming at showing that we can fully exploit the compression capability of random projections to develop an inverse algorithm capable of dealing with the whole IASI spectrum, therefore with minimal loss of information content. The results is a final retrieval with improved precision and horizontal spatial and temporal resolution. Retrieved parameters and species include, surface temperature and emissivity (spectrum), Temperature, H_2O, O_3, HDO, CO_2, N_2O, CO, CH_4, SO_2, HNO_3, NH_3, OCS, CF_4 atmospheric profiles. The effective vertical resolution of these profiles is depending on the degrees of freedom.

A retrieval case study has been set up, which includes thousands of observed spectra for a two-year period (January 2014 to December 2015) over sea surface in the Pacific Ocean close to the Mauna Loa (Hawaii) validation station. Results obtained until now (see e.g. *Liuzzi et al* 2016) show that retrieval of gas species is obtained with unprecedented precision and spatial resolution, which open the way to study and understand regional patterns of greenhouse gases due to anthropogenic activities and/or natural events. In the present study, IASI retrieval for CO_2, CH_4 and N_2O are compared to operational products from different satellites and instruments. These include AIRS (Atmospheric Infrared Radiometer Sounder), GOSAT (Greenhouse Gases Observing Satellite), OCO-2 (Orbiting Carbon Observatory-2). The comparison shows that our retrieval methodology is by far superior to those of existing methods insisting on instruments, which covers the thermal infrared such as IASI, AIRS and GOSAT. Comparison with OCO-2 shows comparable results, but our methodology uses much less a-priori information than OCO-2.

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Ammonia detection using TIR band of GOSAT

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Atmospheric ammonia is emitted from various sources such as food production, wastes, and biomass-burning and their emission amount has been increasing rapidly with the population. It is reported that it has the large impacts on the environments, for instance, the formation of particulate matter or cloud condensation nuclei (CCN) in the atmosphere, and the eutrophications of rivers and lakes. However, the accurate estimation of its behavior is difficult because their life time in the atmosphere is not so long. Space-borne hyper-spectral TIR sounders enable to monitor them globally. Clarisse et al. (2009) had reported the global concentration distribution using the brightness temperature difference at the ammonia absorption band in the thermal infrared region. The similar studies are also reported using the other sounders, TES, AIRS, and CrIS. Although they had captured the seasonal variations of the concentrations, the shorter time-scale phenomena can be hardly detected because of their revisit cycle of 16 days. On the other hand, GOSAT which has the shorter revisit cycle of 3 days has the potential to reveal short time-scale events. The retrieval algorithm was developed based on the non-linear optimal estimation (Rogers, 2000) and the scaling factor to the U. S. standard ammonia profile is estimated as the parameter. As uncertainty in temperature and water vapor profiles causes large estimation error, they are estimated from GOSAT-TIR data in advance. In addition, dust aerosols possibly contaminate the retrievals because of their optical properties. We applied dust detection using TIR slicing method and effectively removed the scans contaminated. The results showed that GOSAT data resolved the short time scale variations in the order of one or two weeks. Ammonia concentrations were especially enhanced over the northern part of India in the summer season and over West Siberia in a period from July to August in 2010. They are respectively attributed to the livestock industry and increase of biomass burning caused by the heat wave.

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Implementing a PCA-based Fast Radiative Transfer Method for XCO_2 Retrievals

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A major challange for remote sensing of XCO_2 from shortwave-infared spectral measuements from satellite missions such as GOSAT and OCO-2 is the development accurate retrieval algorithms that can keep up with the quickly-growing volume of data (from 8,000 clear-sky scenes per day for SCIAMACHY, up to 200,000 for NASA's OCO-2). This necessitates acceleration methods that reduce the computational effort for RT calculations, while at the same time retaining a high level of accuracy of the forward model.

The fast radiative transfer (RT) method based on principal component analysis (PCA) makes use of the large amount of information redundancy within the spectral range of an absorption band that is present in the optical properties (*Natraj et al., 2005*). In this method, representative profiles of the optical properties are inferred from PCA for which high-accuracy RT calculation are carried out. Together with fast, low-accuracy (two-stream) line-by-line calculations, the TOA radiances can be then be reconstructed.

Using a global ensemble of realistic simulations, we have characterised the retrieval errors for GOSAT XCO_2 retrievals intruded by the PCA-based RT calculations and we find that XCO_2 errors are within 0.1 ppm when 3 empirical orthogonal functions (EOFs) are used (for 95 percent of the scenes) (*Somkuti et al., 2017*). A major strength of the PCA-based method is that the errors still remain small even for very challenging scenes with high aerosol loading while yielding a speed-up of roughly two orders of magnitude. Additionally, we also study the accuracy of the method for several different instrument configurations.

Finally, the PCA-based fast radiative transfer method including Jacobians was implemented in the UoL retrieval algorithm and applied to measurements by OCO-2 for overpasses over TCCON stations and we will show some first results.

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Assessment of the aerosol induced biases in the ESA Greenhouse Gas CCI satellite CO_2 products

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Aerosols have been identified as an important factor causing biases in satellite GHG products. To obtain accurate XCO_2 observations from a satellite requires that highly scattering aerosol scenes are correctly identified and filtered out, and that the aerosol effects for the remaining scenes are properly accounted for in the retrieval. In this work the most recent ESA GHG-CCI SCIAMACHY and GOSAT CO_2 products (CRDP4) from four different retrieval algorithms have been assessed. The aim was to investigate to which extent a possible bias in satellite XCO_2 can be attributed to aerosols using multiple linear regression. The dependent variable, the XCO_2 bias (ΔXCO_2), was defined as the difference between satellite and ground-based TCCON XCO_2. The aerosol related explanatory variables were obtained either from ground-based sunphotometer data from the AERONET network, or from satellite-based aerosol observations. The optimal set of explanatory variables for each algorithm and station was obtained by a so-called backward selection method (Fig.1).

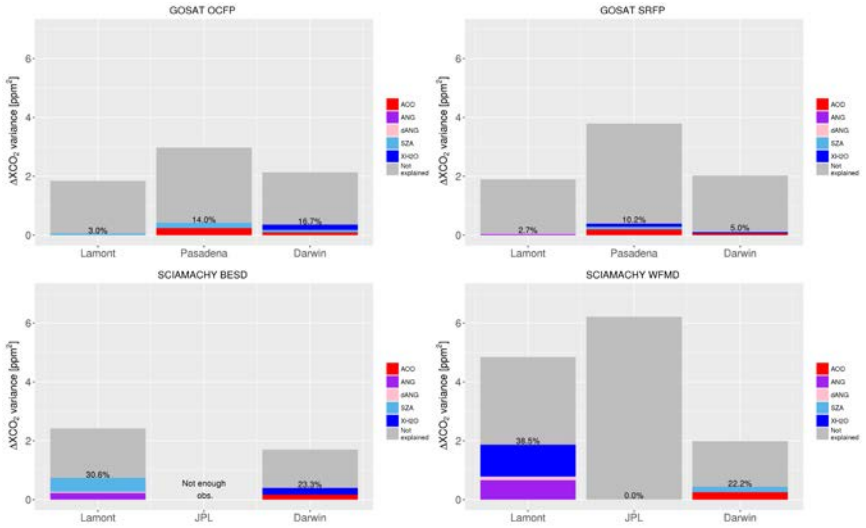

Figure 1: *ΔXCO_2 variances at three different TCCON sites explained by the best linear regression model, when using AERONET-based aerosol data. In each column the grey area represents the unexplained part of ΔXCO_2 variances whereas the colored part represents the variance explained by the regression model. For each model also the R^2_{adj} is shown (in percentages). The explanatory variables are colored as follows: aerosol optical depth AOD (red), Angström coefficient ANG (violet), derivative of Angström coeff. dANG (pink), solar zenith angle SZA (light blue), and column water vapour XH_2O (blue).*

Our results indicate that the effects of aerosols in the ESA GHG CCI XCO_2 CRDP4 products are relatively small in comparison to the measurement precision. The aerosol contribution to the ΔXCO_2 variance remained mainly below 0.2 ppm^2. However, it is noted that the existing TCCON sites are located in areas with low mean aerosol content. If TCCON observations would be available at locations with higher aerosol loading, different conclusions might arise.

CO_2, CH_4 and CO Retrievals and Validation at NOAA using CrIS on S-NPP and JPSS-1

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The Cross-track Infrared Sounder (CrIS) on Suomi National Polar-orbiting Partnership Satellite (S-NPP) and Joint Polar Satellite System (JPSS)-1 is a Fourier transform spectrometer for atmospheric sounding. CrIS on S-NPP started to provide measurements of 2211 channels after switching its mode from normal to full spectral resolution (FSR) mode on December 4, 2014[1], and the spectral resolutions for all three bands, i.e the LWIR band (650-1095 cm^{-1}), the MWIR (1210-1750 cm^{-1}) and SWIR bands (2155-2550 cm^{-1}) are 0.625 cm^{-1} . Such spectral resolutions are the same as in JPSS-1, making it possible to retrieve atmospheric trace gases since December 4, 2014 to beyond.

CO_2, CO and CH_4 are three traces gases (in addition to ozone) that are listed as Level-1 requirements of the Cross-track Infrared Sounder (CrIS) on JPSS-1. This presentation will introduce the most recent improvement of the retrieval of these gases on basis of the NUCAPS (NOAA Unique CrIS/ATMS Processing System), a retrieval system that is under operation at NOAA's The Comprehensive Large Array-data Stewardship System (CLASS). Some validation and applications of the retrieved CO and CH_4 in transport and emission study will also be covered. The validations include comparison of CrIS products with other satellite products, such as CrIS CO_2 against OCO-2 data, CrIS CO against MOPITT data, as well as CrIS CO_2, CO and CH_4 against AIRS and IASI products. Comparison of CrIS products with ground-based measurements from TCCON and NDACC networks are also made.

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The impact on CH_4 retrieval of GOSAT/TANSO-FTS TIR band from differences in line parameter databases and from the uncertainty of the continuum absorption

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The thermal infrared (TIR) band of Thermal and Near-infrared Sensor for Carbon Observation Fourier Transform Spectrometer (TANSO-FTS) onboard Greenhouse Gases Observing Satellite (GOSAT) observes CH_4 profile at wavenumber range from $1210\ \mathrm{cm}^{-1}$ to $1360\ \mathrm{cm}^{-1}$ including CH_4 ν_4 band. The current retrieval algorithm (V1) uses AER V3.1 line database (*Clough et al.*, 2005) and MT CKD continuum model (*Mlawer et al.*, 2012) to calculate optical depth. The purpose of this study is to assess their impact on CH_4 retrieval from using several line parameter databases and from the uncertainty of the continuum absorption.

We used five line parameter databases: HITRAN2000, HITRAN2004, HITRAN2008, AER V3.2, and HITRAN2012 (*Rothman et al.*, 2005, 2009, and 2013; *Clough et al.*, 2005). The CH_4 line parameters of AER V3.2 databases is made of HITRAN2008 and line mixing parameters. We used 2023 GOSAT TIR spectra (L1B V160.160) observed from March 30, 2010 to September 5, 2011. The CH_4 retrieval using AER V3.2 was the lowest. Maximum difference of zonal mean of CH_4 vertical profiles between AER V3.2 and HITRAN2008 were $10\ \mathrm{ppbv}$ at $500\ \mathrm{hPa}$ in latitude range $-20°$to $20°$. This difference was caused by the line coupling of methane. Retrieved CH_4 difference between HITRAN2000, HITRAN2004 and HITRAN2012 are smaller than $2\ \mathrm{ppbv}$. Retrieved CH_4 using HITRAN2008 was $5\ \mathrm{ppbv}$ smaller than other HITRAN databases.

We assumed $\pm 10\%$ uncertainty in the continuum coefficients of MT CKD model and $\pm 50\%$ uncertainty for the temperature coefficient of the H_2O self continuum. Because the H_2O foreign continuum coefficient has about 10% uncertainty at $1400\ \mathrm{cm}^{-1}$ and the temperature coefficient of the water self continuum of MT CKD model overestimated about 30% compared to that of BPS continuum model at the CH_4 retrieval band (*Paynter and Ramaswamy*, 2011). There exist H_2O self continuum, H_2O foreign continuum, CO_2 continuum, and O_2 continuum in the CH_4 retrieval band. CH_4 retrieval differences from using MT CKD model were $-0.3\ \mathrm{ppbv}$ at $431\ \mathrm{hPa}$ for using 10% larger H_2O foreign continuum and $-0.3\ \mathrm{ppbv}$ at $586\ \mathrm{hPa}$ for using 10% larger H_2O self continuum. CH_4 retrieval differences were $0.1\ \mathrm{ppbv}$ at $262\ \mathrm{hPa}$ for using 10% larger CO_2 or O_2 continuum coefficient.

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TanSat retrieval algorithm and its application on global carbon monitoring from space

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China's carbon dioxide observation satellite (TanSat) has been launched in December 2016. A hyperspectral grating spectrometer onboard the TanSat will monitor the column-averaged CO_2 dry-air mixing ratio (XCO_2) in global. The TanSat retreival algorithm has been developed to approeach the XCO_2 in a highly accuracy and precision reqiurment. The TanSat algortihm has been applied on GOSAT (ATANGO) and OCO-2 measumrent and well optimaized before it applied in TanSat operational data processing. In this study, we introduced the TanSat retrieval experiment and the performance of rertrieval algorithm. The preliminary of TanSat retrival results and Level 2 product is showed as a one of recent scitification achievement of TanSat mission. Addiational application of TanSat algorithm on GOSAT and OCO-2 measumrent, including the data product, valdiation and inter-comaprsion will be introducted.

Progress status of the GOSAT/GOSAT-2 SWIR L2 retrievals

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The Greenhouse gases Observing SATellite (GOSAT) was launched in January 2009, and has been operating for more than eight years. The column-averaged dry air mole fractions of carbon dioxide, methane, and water vapor (XCO_2, XCH_4, and XH_2O) have been retrieved globally from the Short-Wavelength InfraRed (SWIR) spectral data observed with the Thermal And Near-infrared Sensor for carbon Observation - Fourier Transform Spectrometer (TANSO-FTS) onboard GOSAT. During the TANSO-FTS operation, several issues were found, and some of them made small changes to the characteristics of the spectral data. Recently, JAXA reprocessed whole spectral data as FTS L1B V201.202 to unify its characteristics. According to this update, the optics degradation and some empirical parameters used in the retrieval processing are under re-evaluation. The results will be applied 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 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.

3 Validation and Supporting Observations Including Ground Based, Aircraft, and In-Situ Observations

Influence of atmospheric conditions on Arctic column-averaged dry-air mixing ratios of atmospheric methane

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Methane is a potent greenhouse gas, but also an important constituent in atmospheric chemistry. Significant uncertainties still remain in the methane budget; therefore high-quality long-term observations of atmospheric methane are essential for improving our understanding of the processes that drive the changes in atmospheric methane. The main sink of methane is the reaction with the hydroxyl radical (OH) in the troposphere. Additional sinks are due to oxidation in soils, reaction with the chlorine radical (Cl) in the marine boundary layer, and stratospheric loss processes. The stratospheric loss processes (reaction with OH, Cl and atomic oxygen and photodissociation) result in a decreasing concentration with age of air.

The methane sources together with variability in the sinks result in a large variability with latitude and in the vertical profile. The methane concentration profile is sensitive to the tropopause height due to the gradient over the upper troposphere/lower stratosphere region. Especially in the Arctic seasonal variability of methane in the stratosphere has a significant influence on the column-averaged mixing ratio of methane (xCH_4).

This study focuses on the effect of stratospheric conditions and tropopause height on the methane profile. Arctic xCH_4 observations from Fourier transform spectrometers from both TCCON (Total Carbon Column Observing Network, Wunch et al., 2011) and NDACC-networks (Network for the Detection of Atmospheric Composition Change, http://www.ndsc.ncep.noaa.gov/) are used. The data are analysed together with profile data from AirCore soundings (Karion et al., 2010), the HALOE (Russell III et al., 1993) and ACE-FTS (Bernath et al., 2005) instruments. The ECMWF ERA-Interim reanalysis data is used to describe the state of the atmosphere.

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Towards a UK TCCON Station

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A new ground based remote sensing facility for high resolution solar occultation spectroscopy of atmospheric constituents has been setup through a collaborative endeavour between the Space Science and Technology Department of the Rutherford Appleton Laboratory (aka RAL Space) and the UK National Centre for Earth Observation (NCEO). The facility, which has recorded its first data this year, intends to seek accreditation to become part of the Total Carbon Column Observing Network (TCCON) and potentially the Network for the Detection of Atmospheric Composition Change (NDACC).

The site is located at RAL Space on the Harwell campus near Oxford, approximately 100km west of London. The prevailing wind direction for this site is south-westerly and we will mostly observe air coming from the Atlantic, but we expect to measure occasionally also plumes from London.

The site hosts a Bruker IFS120/5 HR Fourier Transform Spectrometer (FTS) which is housed inside an air-conditioned building and has been checked to fulfil the nominal TCCON requirements after upgrade and implementation of an instrument lineshape calibration channel. The FTS has been optimally coupled to a south-facing Suntracker for inputting the atmospherically-transmitted solar radiation.

In this presentation, we will give an overview of the site characteristics, the instrumental setup, and presents some of the first early results produced by the new facility.

Using airborne remote sensing observations to determine emissions of complex CH_4 and CO_2 localised sources

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CO_2 and Methane (CH_4) are the two most important anthropogenic greenhouse gases. Localised emissions of CO_2 and CH_4 from point sources such as power plants and coal mine ventilation shafts or fugitive emissions from fossil fuel exploitation and extraction, as well as landfills are often not readily assessed by current measurement systems. Especially aircraft measurements can be used to enhance our knowledge of these anthropogenic emitters, especially when ground access is limited. A sensor developed to accomplish this task is the optical remote sensing instrument MAMAP (Methane Airborne MAPper). It delivers column-averaged dry air mole fractions of CH_4 (or CO_2) based on absorption spectroscopic measurements in the short-wave infrared region. An achieved precision of about 0.3 % in XCO_2 and XCH_4 allows to determine emissions from point sources. During the last years, measurement and data analysis techniques have been refined and the method has successfully been applied to determine emissions from power plants, coal mines, landfills and oil production sites. Recently, the MAMAP remote sensing measurements were accompanied and supplemented by airborne in-situ measurements of CH_4 and CO_2. The in-situ data has been used to validate the remote sensing data and it was demonstrated that CO_2 and CH_4 emissions from strong and localized point sources and point source clusters can be quantified independently. This presentation will give an overview of recent campaign activities with a focus on fugitive emissions from fossil fuel extraction sites, landfills (*Krautwurst et al. (2016)*) and a cluster of power plants (*Krings et al. (20016)*). From the experience gained and lessons learned, conclusions on future airborne and satellite measurement concepts will be drawn.

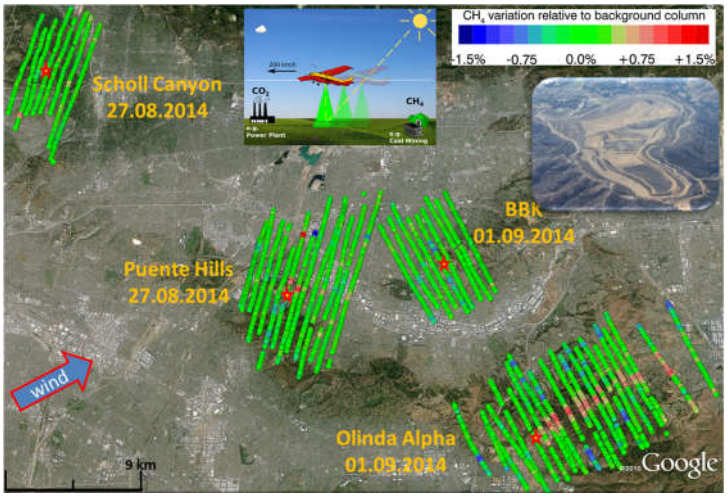

Figure 1: *Overview airborne remote sensing XCH_4 measurements over landfills near Los Angeles, California, details see Krautwurst et al. (2016).*

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Thermal infrared measurements of CO_2 from IASI over the Arctic Ocean in summer and comparison with the CAMS CO_2 inversion product

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The Arctic Ocean is a region where the impact of global change is detected on an annual basis by a wide variety of observations: buoys, research vessels and aircrafts. But the large area involved and the need of frequent sampling make polar orbiting satellites a prime source of observations for documenting the corresponding fast changes, especially in summer. Sun reflected measurements in the shortwave infrared (SWIR) region of the spectrum are not very sensitive because of the elevated solar zenith angle. In these conditions,

Thermal infrared (TIR) measurements using spectra collected by high spectral resolution nadir sounders are a good complement to document the high latitudes regions. In the present work the spectra acquired by the IASI instrument on the MetOp platforms have been used to test the retrieval capabilities of these Fourier transform spectrometers to retrieve the carbon dioxide column averaged mixing ratio XCO_2 as well as the sea surface temperature (SST) used as an inversion diagnostic. Results for 3 observing periods in summer (July, August, September) and 6 years (2010 to 2015) have been obtained in the latitude range 68N to 82N over open water (no pack ice). The retrieved products have been analyzed from a climatologic point of view to assess inter-annual variability and trends of TIR derived XCO_2 and SST zonal averages (3 summer months and 7 bins of 2° in latitude). Results will be described and compared to the results from the CAMS inversion product that assimilated surface measurements. A discussion of the possible origin of bias between IASI measurements and CAMS XCO_2 will be presented. Specific regional basins of the Arctic Ocean in summer will be discussed in relation to climate change issues.

Keywords: IASI, carbon dioxide, XCO_2, SST, retrieval, satellite-model comparison, climatology

Presentation preference: oral

Terrestrial and airborne optical analyzers for the detection of greenhouse gases

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In order to validate satellite data, several measurements can be necessary, carried out in different environmental conditions, mainly altitude above the sea level, latitude, presence of hot spots, etc.
It makes a big deal of difference when the measurements are done on the ground, or on board of a stratospheric platform (aircraft or balloon), or at the edge of a volcan, or close to a methane extraction site in a desert area. For these reasons, validation of satellite measurements requires a set of different devices, tailored on the particular experimental conditions of expected concentration, resolution, accuracy, temperature, pressure, humidity, presence of aggressive constituents of the atmosphere.

We report here on our most recent set of optical gas analyzers, developed for in situ detection of trace gases in the upper troposphere - lower stratosphere, and in volcanic emissions. The analyzer installed on board of the stratospheric platform M55 "Geophysica", named COLD (Carbon Oxide Laser Detector, Fig. 1 left), presently measures CO but, by just changing the set point of the laser, can measure N_2O, both at a level of a few ppb. When changing the laser, several other molecules can be targeted.

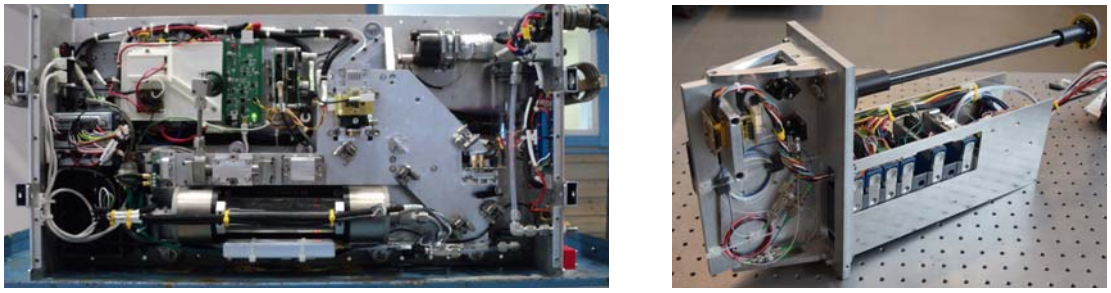

Figure 1: *COLD analyzer (left) and CO_2/HF analyzer (right)*

Three more gas analyzers have been realized, for the detection of HCl (absolute concentration and isotopic ratio $H^{37}Cl/H^{35}Cl$), CO_2 and HF (Fig. 1 right), and SO_2. These devices aim to the detection of a GHG and pollutant molecules in hotspots like volcans.
All of these instruments feature low weight and power consumption (the devices for volcans are battery operated), and the specific characteristics to face the environmental conditions: low pressure and temperature, vibrations in the stratosphere; aggressive chemicals near volcans.
Detectivity limits are quite different according to the gases: ~ 1 ppb for CO, ~ 20 ppb for the acids, ~100 ppb for SO_2, ~ 1 ppm for CO_2 (with a concentration of the order of 1000 ppm).

Acknowledgments: COLD instrument has received funding from EC FP7/2007-2013 under grant agreement n° 603557, Project STRATOCLIM; the analyzers for volcans have been developed within FP7-IDEAS-ERC Project CO2Volc (Grant 279802).

Comparison of X_{CO2} and X_{CH4} measurements from three solar FTIR instruments at Wollongong, Australia

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The Total Carbon Column Observing Network (TCCON) was established in 2004 with the primary aim of producing high precision and accuracy measurements of column-averaged mole fractions of greenhouse gases. TCCON fulfils three scientific roles: satellite validation, for instruments such as the Greenhouse Gases Observing Satellite (GOSAT) and the Orbiting Carbon Observatory-2 (OCO-2); independent validation of model simulations driven by satellite or *in situ* measurements; and providing insight into the global carbon cycle. The core of these sites is a high resolution Bruker IFS125HR Fourier Transform Spectrometer, an instrument that is capable of high spectral resolution and excellent precision and consistency between sites; however, these instruments are both expensive and difficult to transport.

Recently, several more portable alternative instruments to the standard TCCON configuration have become available. Comparison between a number of these lower spectral-resolution instruments is the subject of the project *Fiducial Reference Measurements for Ground-based Infrared Greenhouse Gas Observations* (FRM4GHG), taking place at Sodankylä, Finland during 2017. These instruments are suitable for deployment on a campaign basis and more suited to short-term scoping studies than a full TCCON station. The most widely used to date, the Bruker EM27/SUN, shows good short-to-medium term stability relative to TCCON, but is not yet tested on long-term time scales, nor well set up for remote, automated operation. At the Wollongong TCCON station, an EM27/SUN has been operational alongside the standard instrument over a period over several years, along with an in house developed instrument based on a Bruker IRCube ("FibreCube") utilising a fibre optic cable to transfer the solar image from the tracker to the spectrometer.

Here we present a comparison between the EM27/SUN, the FibreCube, and TCCON measurements of X_{CO2} and X_{CH4} at Wollongong, Australia. This comparison includes periods over several years, and includes studies of the effect of instrumental changes to the FibreCube, therefore allowing quantification of its sensitivity to operational parameters.

The CCI-GHG CRDP#4 : Validation using TCCON

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Various institutions

The Greenhouse Gas Climate Change initiative (GHG-CCI) project's (www.esa-ghg-cci.org) goal is to generate global data sets of satellite-derived Essential Climate Variables (ECVs) for XCO_2 and XCH_4 with a quality sufficient to obtain information on regional sources and sinks. The project delivers time series for both SCIAMACHY on ENVISAT (2002-2012) and TANSO-FTS onboard GOSAT (2009 onwards) from several European algorithms developed by the University of Bremen, the University of Leicester and SRON Netherlands Institute for Space Research (*e.g. Buchwitz et al., 2016*). Here we present validation results from the latest products in the so-called Climate Research Data Package #4 (*Buchwitz et al., 2017*) with ground-based remote sensing measurements from the TCCON (*Wunch et al.,2011*). We'll specifically look at where algorithms differ and to what extent these difference can be deemed statistically significant.

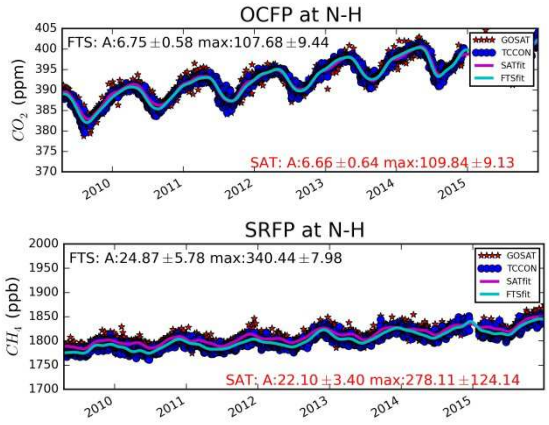

Figure 1: *Northern Hemisphere abundances of University of Leicester's Full Physics OCFP XCO_2(top) and SRON's Full Physiscs (SRFP) XCH_4 (bottom) compared to TCCON*

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[**)] see https://tccon-wiki.caltech.edu/Network_Policy/Data_Use_Policy

Validation of Carbon Monoxide Total Columns from SCIAMACHY mission with NDACC/TCCON

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Carbon monoxide is a key species of Earth's atmosphere. Accordingly, a number of spaceborne sensors are observing the species in the infrared and microwave. For the analysis of short wave infrared spectra measured by SCIAMACHY and similar instruments we had developed the Beer InfraRed Retrieval Algorithm: BIRRA is a separable least squares fit of the measured radiance with respect to molecular column densities and auxiliary parameters (optional: surface albedo, baseline, slit function width, and wavenumber shift). BIRRA has been implemented in the operational SCIAMACHY L1 to 2 processor for the retrieval of CO and CH4 from channel 8 and 6, respectively; the validation study reported here is based on the BIRRA prototype version giving more flexibility.

Verification and validation are critical elements of any code development, and mandatory for the assessment of spaceborne remote sensing products. In this poster we report on intercomparisons of CO columns estimated from SCIAMACHY with temporal coincidented and co-located retrievals provided by ground-based Fourier transform infrared spectroscopy. More specifically, we have used column averaged dry air mole fractions from several NDACC (Network for the Detection of Atmospheric Composition Change) and TCCON (Total Carbon Column Observing Network) stations. Like SCIAMACHY's channel 8 the TCCON instruments utilize the 2.3 mue band of carbon monoxide, whereas NDACC observes the CO mid infrared absorption. In most cases, satellite validation is based on statistical comparison (specifically true for SCIAMACHY with its large signal to noise ratio per observation (*Gimeno García et al.* 2011) with reference data. However, satellite and reference measurements do neither exactly match in time and space (mistime and misdistance) nor address the same volume of air (misintegration). Hence, the natural atmospheric variability leads to differences between both data sets. These differences must not be interpreted in terms of a satellite's instrument malfunction (*Verhoelst et al.* 2015). The validation strategy presented here accounts for both, temporal or spatial induced mismatches.

Increased deviations of the spaceborne and ground-based columns in the later years of the mission clearly demonstrate the impact of the degrading channel 8 detector. Therefore, in order to perform a comprehensive full-mission (2003 – 2012) validation of the SCIAMACHY dataset, an approach providing more observations within a given time interval and sampling area has been utilized.

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Bias correction in CH_4 flux inversions using satellite data and the role of atmospheric transport

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Global CH_4 flux inversions making use of both surface and satellite measurements generally require a bias correction to account for systematic inconsistencies in the information provided by both data sets. In principle, such inconsistencies may arise either from systematic errors in the data or in the atmospheric transport model used to fit the data, or both. Interestingly, the bias corrections reported in several inverse modelling studies using GOSAT XCH4 retrievals show similar latitudinal dependences. A better understanding of the origin of this bias is crucial to be able to improve our understanding on tropical versus extra-tropical emissions of methane. Satellites greatly improved the measurement coverage over tropical land, but the need for latitudinal bias correction functions substantially limits their added value.
In this study, we investigate the hypothesis that the bias is caused by inaccuracies in the modelling of stratosphere – troposphere exchange. Earlier studies suggested that seasonal and latitudinally varying errors in the simulated age of air in the stratosphere could explain the shape of the bias correction functions. This finding is supported by comparisons of inverse modelling optimized concentrations and measurements from the HIPPO campaigns, showing the largest discrepancies near the mid latitude tropopause.
To further investigate these findings, we analyzed the vertical gradient of CH_4 near the tropopause and into stratosphere as simulated by the global atmospheric Tracer Model 5 (TM5), in comparison with simulations from the Integrated Forecasting System (IFS) and Aircore measurements. Results will be shown for methane and carbon dioxide to separate influences from stratospheric transport and chemistry on the vertical profile of methane.

FTS measurements of greenhouse gases over Sodankylä

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In Sodankylä (67.4° N, 26.6° E) we have performed Fourier Transform Spectrometer (FTS) measurements since early 2009 (*Kivi and Heikkinen, 2016*). Our FTS instrument participates in the Total Carbon Column Observing Network (TCCON) and in validation of satellite borne instruments. The measurements of dry-air column-averaged carbon dioxide mixing ratio (XCO_2) and methane mixing ratio (XCH_4) since early 2009 are presented here using the TCCON retrieval version GGG2014. We also provide comparisons with the satellite based observations, including the Greenhouse gases Observing SATellite (GOSAT) and the Orbiting Carbon Observatory-2 (OCO-2). In average we find good agreement with the space borne measurements. The data can be used for validation purposes of also other satellite missions, such as TROPOMI on board ESA Sentinel-5P satellite and Chinese TanSat.

In addition to the FTS measurements we have performed in situ AirCore measurements at Sodankylä (*Tukiainen et al., 2016*). AirCore is a balloon borne sampling system, which provides the accuracy of 0.05%, regarding the CO_2 and CH_4 observations. The measurements are directly related to the World Meteorological Organization in situ trace gas measurement scales. The AirCore system at Sodankylä provides tropospheric and stratospheric profiles, with the current configuration of the instrument vertical resolution in the stratosphere is 5 mb and vertical resolution in troposphere is 15 mb. Near the surface we have obtained continuous measurements by a Picarro analyser, which is installed in the vicinity of the TCCON instrument.

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Fiducial Reference Measurements for Ground-Based Infrared Greenhouse Gas Observations (FRM4GHG) campaign at the Sodankylä TCCON site

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Recently several new portable spectrometers have become available, however the performances of these instruments have not been fully characterized. The ongoing ESA funded campaign "Fiducial Reference Measurements for Ground-Based Infrared Greenhouse Gas Observations (FRM4GHG)" at the Sodankylä TCCON site aims at characterizing several of the portable spectrometers. During the campaign the TCCON type measurements (*Wunch et al., 2011*) are run under various atmospheric conditions to provide comparisons with the reference TCCON instrument. The remote sensing measurements are accompanied by AirCore (*Karion et al., 2010*) launches from the Sodankylä site. The AirCore in situ reference profiles will be used to verify the calibration of the remote sensing instruments involved.

The campaign focuses on CO and CH_4 measurements in support of the ESA Sentinel-5P validation. In addition also CO_2 will be retrieved and other gases. Thus the campaign data can be used for validation purposes of also other satellite measurements and model simulations. The results are expected to provide a comparative characterization of the participating instruments with respect to the TCCON instrument. The outcome of the campaign will be used for the further development of new observation sites to complement the TCCON network and improve support for the validation of the existing and future satellite missions and models. Here we provide an overview of the campaign objectives and instrumentation as well as the first results of the measurements, which have been obtained since the start of the campaign in March 2017.

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Integrated Carbon Observation System (ICOS) Research Infrastructure provides atmospheric GHG data for scientist

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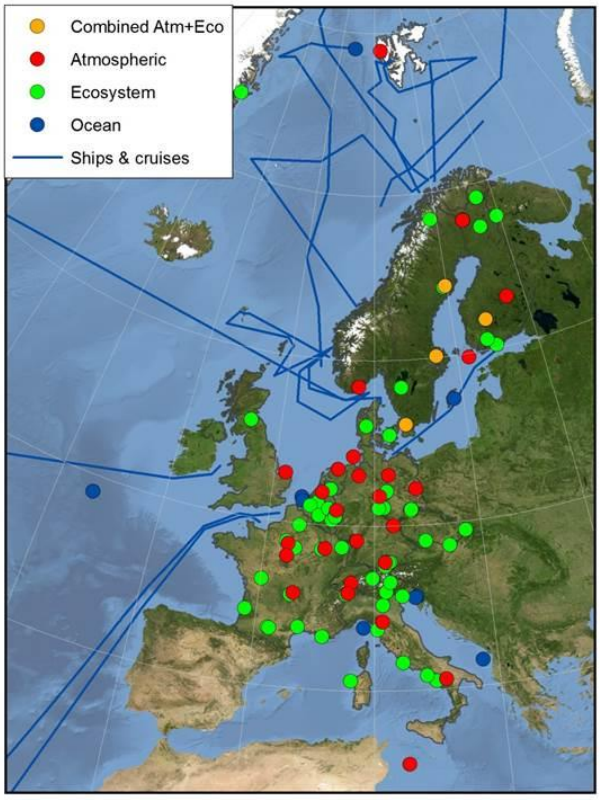
The aim of ICOS RI is to provide for researchers and society near real time data of long-term observations of greenhouse gas fluxes from ecosystems and oceans, and greenhouse gas concentrations in the atmosphere. ICOS RI consists of national measurement networks and European coordinating units. There are thematic centres for atmospheric, ecosystem, ocean measurements, central analytical laboratory, and carbon portal for data distribution. Head Office is located Helsinki. ICOS RI coordination activities ensure that the measurements are processed into coherent data sets which are easily available to the researchers. The ICOS central facilities collect, process and store in near real time the data measured at the stations of ICOS national networks. The standardization and coordination ensure the accuracy and global compatibility of the observational data. The data are made available through the Carbon Portal. ICOS RI has more than 100 measurement stations in twelve European countries. The number of participating countries is increasing fast. Presently ICOS processes in-situ atmospheric greenhouse gas concentrations. In a supporting Horizon 2020 project Ringo there is a task to make a scientific and technical evaluation how to bring within ICOS European total column GHG observations conducted in TCCON network. We will present ICOS Research Infrastructure and what kind of data products it will offer for atmospheric scientists.



Assessment of the satellite-measured seasonal cycles of XCO_2 from GOSAT and OCO-2

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The seasonal cycle accounts for a dominant mode of total column CO_2 (XCO_2) annual variability and is connected to CO_2 uptake and release; it thus represents an important quantity to test the accuracy of the measurements from space. For this, the ground-based retrievals of XCO_2 from the Total Carbon Column Observing Network (*Wunch et al.*, 2011) provide an ideal and independent validation resource. In our poster, we summarize the results from *Lindqvist et al.* (2015), where we quantitatively evaluate the XCO_2 seasonal cycle of the GOSAT ACOS B3.5 retrievals and compare average regional seasonal cycle features to those derived from 1) the TCCON measurements, 2) other GOSAT retrievals at the TCCON sites, and 3) optimized XCO_2 fields from models that assimilate in situ measurements of CO_2. In addition to this summary, we update the seasonal cycle analysis for GOSAT ACOS B7.3, and provide a preliminary look towards the seasonal cycle from the first two years of OCO-2 observations. Our results provide an estimate on the accuracy of the seasonal cycles of space-based XCO_2 retrievals, which is essential ground work for further studies on seasonal variability of regional XCO_2.

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Atmospheric CO_2 Concentration Measurements to Cloud Tops from an Airborne Lidar

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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. 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 XCO_2 and range to cloud tops in addition to those to the ground with precise knowledge of the photon path-length.

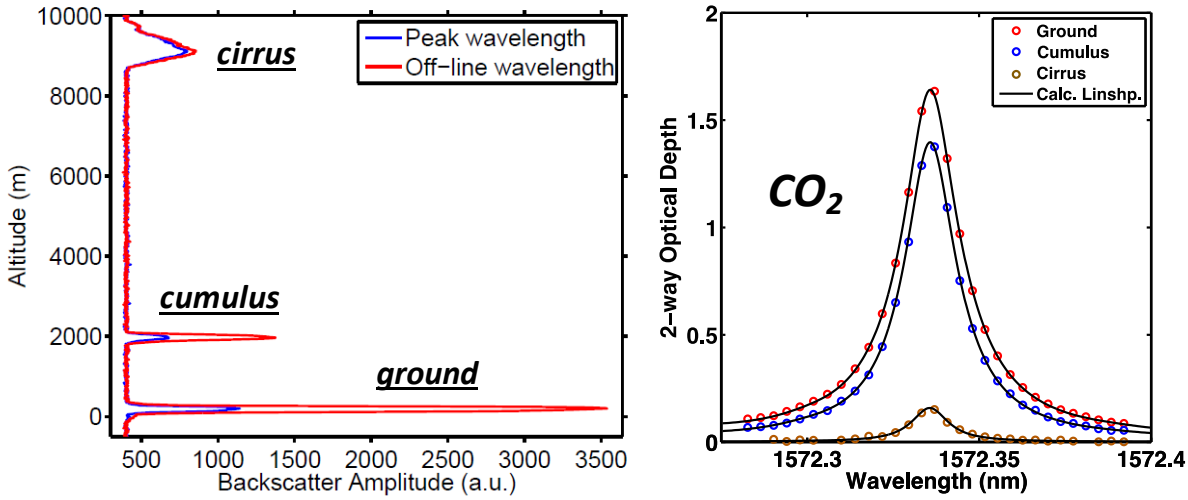

Figure 1: *Example of airborne lidar measurements of backscatter profile (right panel) and CO_2 absorption line shapes in terms of optical depth (left panel) for laser returns from ground, cumulus clouds and cirrus clouds.*

We demonstrate this measurement capability using airborne lidar measurements from 2011, 2013 and 2014 ASCENDS airborne science campaigns. We show retrievals of XCO_2 over low-level marine stratus clouds, cumulus clouds at the top of planetary boundary layer, some mid-level clouds, and visually thin high-level cirrus. The XCO_2 retrievals from the lidar are validated against in situ measurements and compared to the Goddard Parameterized Chemistry Transport Model (PCTM) simulations.

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.

Validation of physical inverse products from IASI spectra: the case of Carbonyl Sulphide (OCS).

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The importance of carbonyl sulphide in the study of ecosystems has clearly emerged in recent studies. OCS is the most abundant sulphur-containing trace gas in the atmosphere, and carries a significant part of sulphur in the stratospheric aerosol. Major sources of OCS are natural, and among them oceans, soils and volcanic eruptions play a dominant role. Otherwise, anthropogenic sources have been recognized as a secondary contributor: the most important of them are biomass burning and industrial activities. The main sink of OCS has been identified as vegetation uptake, whose magnitude is also influenced by seasonal trends in vegetation growth. Conversely, in the stratosphere photochemical loss is the prominent process that remove OCS from the atmosphere. OCS has recently emerged as a putative proxy for the photosynthetic uptake of CO_2, because OCS and CO_2 have the same diffusion pathway into leaves, and OCS hydration reaction in this process is irreversible. The quantification of OCS concentration above forest canopy is also of primary interest to obtain indications about the direct impact of photosynthetic processes on the CO_2 seasonal and inter-annual trends. Therefore, the capability of IASI (Infrared Atmospheric Sounder Interferometer) for retrieving the seasonal cycle of OCS is an important asset. Recent studies have shown that carbonyl sulphide holds great promise for studies of carbon cycle processes because it is an atmospheric tracer of photosynthetic Gross Primary Production (GPP). Results from the physical, simultaneous, inversion of the full IASI spectrum (see *Liuzzi et al.* 2016) applied to the retrieval of surface temperature and emissivity, temperature, water vapour, ozone and HDO vertical profiles, and gas column abundance of CO_2, CO, CH_4, SO_2, N_2O, HNO_3, NH_3, OCS and CF_4 have been updated with respect to the validation of OCS products. The scheme can exploit the full IASI information, since we consider the whole IASI spectral coverage. Model parameter error is minimized by resorting to a simultaneous retrieval in which all the parameters relevant to the formation of the IASI spectrum are retrieved together with OCS. We use *random projections* (see *Serio et al.* 2016) to reduce the dimensionality of the data space and to have a unified treatment of instrument and forward model errors. The OCS column amount is retrieved by using a non-parametric approach, in which we first derive the OCS profile and then its global amount is estimated by a proper integration over the profile. IASI OCS retrievals are compared to *in situ* flask observations at the Mauna Loa validation station, Hawaii, USA and observations from HIAPER Pole-to-Pole flights. We have found that the IASI can retrieve OCS cycle amplitude, phase and mean abundance with high accuracy for night and day time soundings. In fact, IASI captures the OCS seasonal cycle, with an overall difference with *in situ* observations, which is of the order of ≈ 1 pptv. An application of the scheme to land surface is considered as well, showing that IASI can also retrieve the OCS cycle in case of ecosystems where the OCS cycle is governed by leaf and/or soil sources/sinks. The paper demonstrates that IASI can potentially distinguish between leaf and soil sinks of OCS.

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Philippines TCCON installation: towards quantifying atmospheric carbon in Southeast Asia

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The Total Carbon Column Observing Network (TCCON) is dedicated to the precise measurements of greenhouse gases 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 greenhouse gas emissions, TCCON has taken on a vital role in validating satellite-based greenhouse gas data from past, current and future missions like Japanese GOSAT and GOSAT-2, NASA's OCO-2 and OCO-3, Chinese TanSat, and others. The lack of reliable validation data for the satellite-based greenhouse gas observing missions in the tropical regions is a common limitation in global carbon-cycle modeling studies that have a tropical component. The international CO_2 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. A TCCON site in the western tropical Pacific is a logical next step in obtaining additional knowledge that would greatly contribute to the understanding of the Earth's atmosphere and better constraining a major tropical region experiencing tremendous economic and population growth.

An assessment for possible sites in the Philippines where TCCON FTS should be installed was performed and we decided to install it at Burgos site (the substation of Energy Development Corporation Burgos Wind Farm Project), Ilocos Norte, Philippines (18.5326° N, 120.6496° E). We characterized a performance of the newly constructed TCCON instrument intended for deployment to the Philippines and made initial measurements at the NIES compound in Japan. After development in Japan, we deployed TCCON FTS at Burgos site in Dec. 2016 and conducted installation/set up of instruments until Mar. 2017. Then we could get the first light measurements in Philippines. Here, we will present the whole picture of the Philippines TCCON project.

GreenLITE™: A Novel Approach to Ground-Based Quantification and Mapping of Greenhouse Gases with Potential for Validation of Low Bias Lidar Measurements Needed for Space

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First demonstrated in 2013, GreenLITE™ is a novel system developed by Harris and its partners at Atmospheric Environmental Research, Inc. that allows for real-time two-dimensional continuous mapping and quantitative data analytics of greenhouse gas (GHG) emissions from sites of varying size in remote, urban, and industrial environments. GreenLITE uses two fixed-point laser transceivers in conjunction with a series of retroreflectors strategically placed around the site of interest. Based on integrated path differential absorption lidar techniques, each transceiver simultaneously transmits a multi-wavelength continuous wave (CW) laser signal and receives light that is reflected from any given retroreflector. Leveraging previous development efforts of Harris' Multi-Functional Fiber Laser Lidar (MFLL), an airborne demonstration unit built for the ASCENDS mission and currently a primary instrument on the NASA Earth Venture Suborbital mission ACT-America, the received signals are discerned from background noise through an intensity-modulated approach (IMCW). From measurements of the differential laser power that is absorbed along a specific chord defined by the transceiver unit and retroreflector, the dry air mixing ratio or concentration of the atmospheric gas being sensed is then deduced from well-established atmospheric radiative transfer models using meteorological data collected at each transceiver.

Originally designed for monitoring CO_2 levels across carbon sequestration sites, GreenLITE has also successfully been deployed for year-long continuous measurements of urban CO_2 levels over Paris, France. More recently, development efforts have focused on adding capabilities for open-path CH_4 measurements. These include adapting GreenLITE to small industrial sites for monitoring both fugitive emissions and large-scale leakage events and quantifying total flux of GHG emissions. Preliminary results from field tests conducted in late 2016 have shown GreenLITE CH_4 concentration measurements in agreement to within 0.5% of background (~10 ppb) with a single-point in situ instrument calibrated against a World Meteorological Organization (WMO) traceable gas standard.

In addition to terrestrial applications, GreenLITE is currently being explored as a vehicle for validating open-path GHG lidar measurements for air and space. Recent proposals have included potential cross-calibration efforts at well-characterized field sites of GreenLITE with other open-path lidar instrument concepts such as dual comb laser spectroscopy developed by the National Institute of Standards and Technology (NIST) in the United States, *Rieker et al.* (2014). Such efforts are important for validating and understanding the limits of next generation instrument concepts for GHG measurements from space, such as a space-based implementation of MFLL that is currently being investigated.

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Aerosol Scattering Effects on Water Vapor Retrievals over the Los Angeles Basin

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We propose a novel approach to describe the scattering effects of atmospheric aerosols in a complex urban environment using water vapor (H_2O) slant column measurements in the near infrared. This approach is demonstrated using measurements from the California Laboratory for Atmospheric Remote Sensing Fourier Transform Spectrometer on the top of Mt. Wilson, California, and a two-stream-exact single scattering radiative transfer (RT) model. From the spectral measurements, we retrieve H_2O slant column density (SCD) using 15 different absorption bands between 4000 and 8000 cm^{-1}. Due to the wavelength dependence of aerosol scattering, large variations in H_2O SCD retrievals are observed as a function of wavelength. Moreover, the variations are found to be correlated with aerosol optical depths (AOD) measured at the AERONET-Caltech station (see Figure 1). Simulation results from the RT model reproduce this correlation and show that the aerosol scattering effect is the primary contributor to the variations in the wavelength dependence of the H_2O SCD retrievals. A significant linear correlation is also found between variations in H_2O SCD retrievals from different bands and corresponding AOD data; this correlation is associated with the asymmetry parameter, which is a first-order measure of the aerosol scattering phase function. The evidence from both measurements and simulations suggests that wavelength-dependent aerosol scattering effects can be derived using H_2O retrievals from multiple bands. The understanding of aerosol scattering effects on H_2O retrievals suggests a promising way to quantify the effect of aerosol scattering on greenhouse gas retrievals and could potentially contribute towards reducing biases in greenhouse gas retrievals from space.

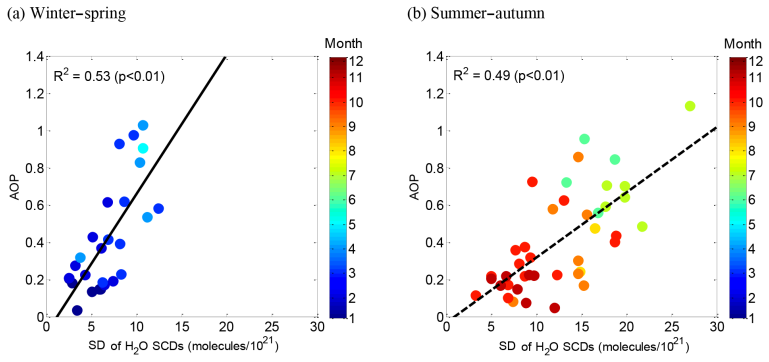

Figure 1: *Correlation between daily averaged standard deviation of H_2O SCDs, a measure of retrieval differences, from 12:00 to 14:00 LT, and the corresponding averaged AOP, calculated by scaling AOD data (1020 nm) from AERONET based on CLARS geometry, for two time periods in 2013. (a) Winter and spring. (b) Summer and autumn. In total, there are 68 days of daily mean data available in 2013, out of which 27 days are for winter–spring and 40 days are for summer–autumn.*

Ground-based measurement of column-averaged mixing ratios of carbon dioxide in Tokyo by a portable optical spectrum analyzer

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The metropolitan area in Tokyo, the capital of Japan, emits a large amount of the anthropogenic greenhouse gas, carbon dioxide (CO_2). A portable ground-based instrument consisting of a commercially available desktop optical spectrum analyzer and a compact sun tracker has been applied to measurement of solar absorption spectra to obtain the column-averaged dry-air molar mixing ratios of atmospheric CO_2, XCO_2, in the central area of Tokyo from August 2014 to June 2016. The characteristic diurnal variations in XCO_2 are interpreted in terms of the local surface meteorological data. The observed seasonal trend in XCO_2 is compared with the reported data of either the GOSAT satellite or in situ surface measurements at the ground for the areas of the central and vicinity of Tokyo.

Update on OCO-2 Validation Using TCCON

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NASA's Orbiting Carbon Observatory 2 (OCO-2) satelllite was successfully launched on July 2, 2014 and has been measuring column-averaged dry-air mole fractions of carbon dioxide (CO_2) in the Earth's atmosphere for almost three years. These OCO-2 satelllite measurements are validated using TCCON (Total Carbon Column Observing Network), a well established network of ground-based Fourier Transform Spectrometers that record direct solar spectra in the near-infrared and from which 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.

In this work, we will briefly describe the various OCO-2 observational modes, but will focus mainly on the TCCON target mode observations. Target selection criteria, location, and data availability will be discussed. Finally, comparisons between OCO-2 and TCCON will be presented for all OCO-2 observational modes [Wunch et al., 2016]. As an example, Figure 1 shows the correlation between the OCO-2 target mode observations and the coincident TCCON measurements both after a bias correction (left plot) and without correction (right plot).

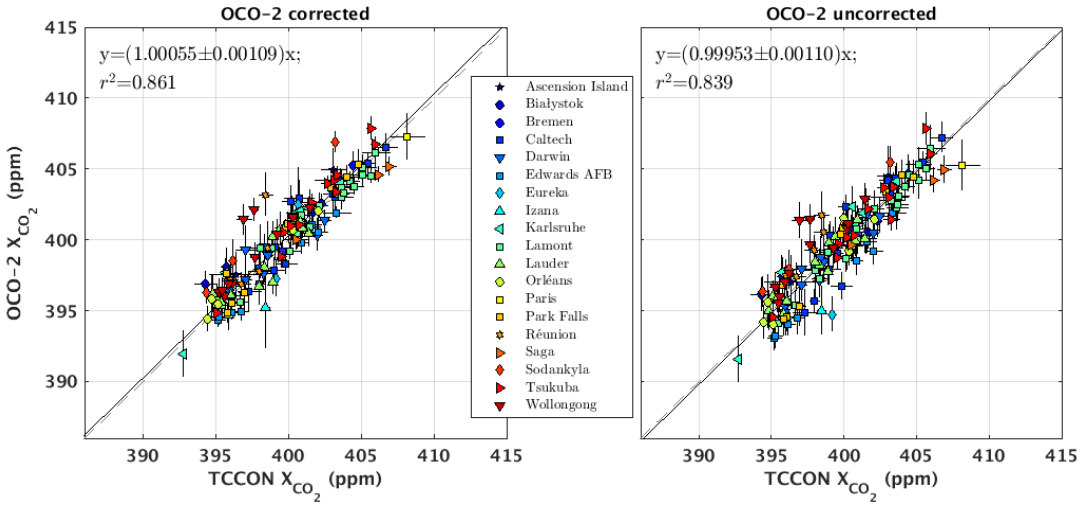

Figure 1: *OCO-2/TCCON vs Target Data Comparison*

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Validation of Level 2 CO_2 and CH_4 products of GOSAT/TANSO-FTS thermal infrared band and future algorithm improvement

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The Greenhouse Gases Observing Satellite (GOSAT) has continued its observations of CO_2 and CH_4 since its launch. We have evaluated biases in CO_2 concentrations retrieved from thermal infrared (TIR) band of Thermal and Near Infrared Sensor for Carbon Observation (TANSO)–Fourier Transform Spectrometer (FTS) on board GOSAT by comparing them with data from the Continuous CO_2 Measuring Equipment (CME) in the Comprehensive Observation Network for TRace gases by AIrLiner (CONTRAIL) project (Machida et al., 2008) and data simulated by the Nonhydrostatic ICosahedral Atmospheric Model (NICAM)-based transport model (TM) (Niwa et al., 2011) in the upper troposphere and lower stratosphere (UTLS), the middle troposphere (MT), and the lower troposphere (LT). In the UTLS region, TIR version 1 (V1) CO_2 data had larger negative biases in spring and summer than in fall and winter in the northern low and middle latitudes, and the biases became larger over time. However, TIR UT CO_2 data displayed seasonal variations that were similar to the CME data, and the amplitudes of their seasonal variations were comparable. In the MT region, TIR CO_2 data had the largest negative biases. Comparisons between NICAM-TM CO_2 data and bias-corrected TIR CO_2 data to which the bias-correction values evaluated over the airports were applied demonstrate the validity of the bias-correction values.
We compared TIR V1 CH_4 data with data obtained over Minamitorishima by a C-130H cargo aircraft (Tuboi et al., 2013; Niwa et al., 2014) and with data obtained in a wide latitude range during the HIAPER Pole-to-Pole Observation (HIPPO) aircraft campaign (Wofsy et al., 2011). The comparison results showed that TIR CH_4 data agreed with the aircraft CH_4 data to within ~1% in the MT and LT regions in the northern middle latitudes in spring, fall and winter, although they had negative biases of 1.2−1.5% in the MT region in summer. TIR CH_4 data in the MT regions agreed with HIPPO CH_4 data to within 1% in low latitudes and in the southern middle latitudes, which is consistent with previous validation results (e.g., Zou et al., 2016).

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Airborne-based demonstration of intelligent pointing onboard GOSAT-2

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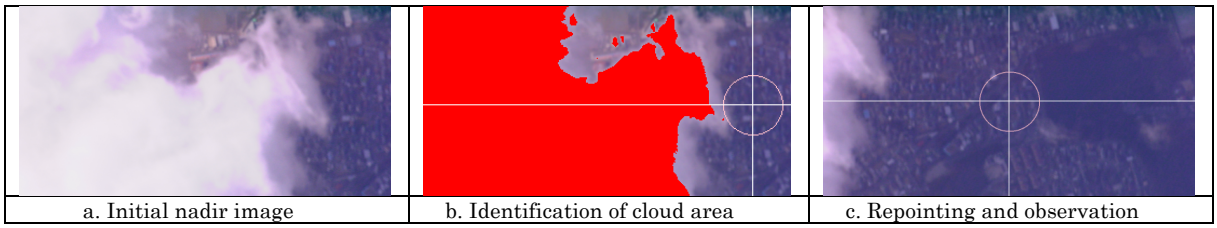
The Greenhouse gases Observing SATellite 2 (GOSAT-2) has been developing to monitor the global CO_2, CH_4 and CO distribution. The innovated pointing system, named intelligent pointing system, will be accommodated on GOSAT-2 to improve the clear sky observation frequency. The idea of intelligent pointing is as follows: capture the science scene image with visible camera, process the cloud area on the captured image, and change the line of sight to avoid cloud area. To demonstrate the newly developed technique with actual cloud and nadir looking condition, airborne-based experiment was carried out in Feburary 2017. The intelligent pointing function is implemented on the nadir-looking pointing system with image motion compensation (IMC) for GOSAT airborne-FTS, called TSUKUBA model. The instruments are mounted on KingAir-200T, and fly over the actual cloud area with 7km flight altitude. The obtained visible camera images of TSUKUBA model are shown in Fig.1. The first image (Fig.1a) suggests us that the field of view for TSUKUBA model (center position in image) is fully covered with cloud. Through the cloud identification, the clear sky area is founded on the right side on image (Fig.1b). The repoint location is processed onboard and commaded the clear sky location and observed the interferogram (Fig.1c). The result suggets us that the intelligent pointing system can improve the clear sky observation frequency. The experimental result will be presented as well as the outlook.



a. Initial nadir image | b. Identification of cloud area | c. Repointing and observation

Figure 1: *Seqeuenc of intteligent pointing with the observed scene image*

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Vertical distribution and time-series of Arctic methane

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In this study we analyze the vertical distribution of atmospheric methane (CH4) measured in Sodankylä, Northern Finland. The CH4 pro les were retrieved from the direct Sun FTS measurements using the dimension reduction retrieval method (Tukiainen et al., 2016). The whole data set covers years 2009 to the present day (from February to November) and altitudes 0-40 km. The retrieved pro les were validated against the ACE satellite measurements and AirCore balloon measurements. In general, a good agreement was found between the retrieved FTS pro les and the reference measurements. The total columns calculated from the pro les were compared with the TCCON XCH4 data. In this comparison the overall agreement was good but there was a signi cant bias between the products. Finally, we analyzed the time-series of methane over Sodankylä (trend and seasonal cycle) using dynamic linear regression. In addition to the time-series analysis, the vertically resolved methane data set can be used, e.g., to study stratospheric methane in polar vortex conditions.

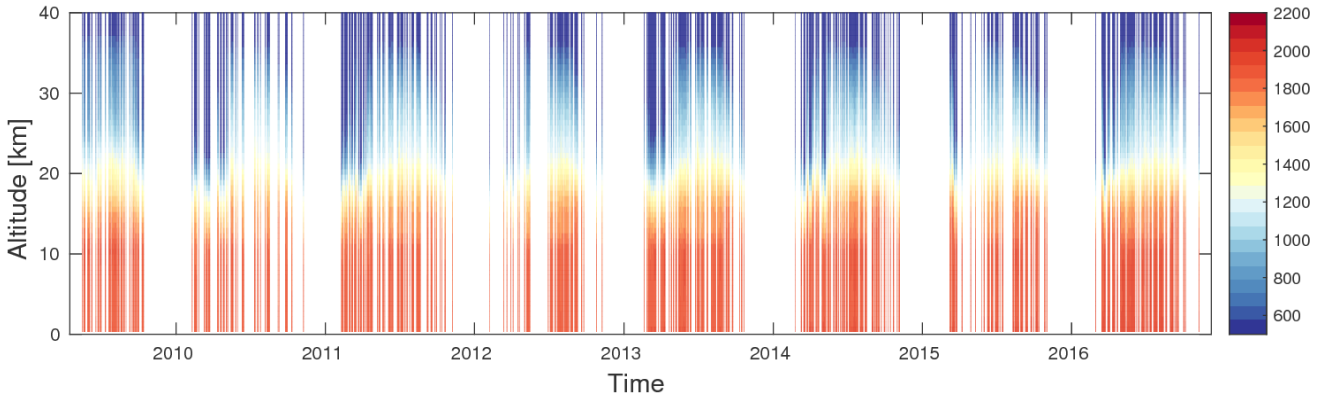

Figure 1. Time-series of the methane pro les measured in Sodankylä.

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Lidar observation at TCCON sites to investigate the influence of particles on GOSAT data

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The Thermal And Near infrared Sensor for carbon Observation-Fourier Transform Spectrometer (TANSO-FTS) onboard the Greenhouse gases Observing SATellite (GOSAT) measures the Short Wavelength InfraRed (SWIR) spectra of sunlight reflected from the earth surface and atmosphere. The column averaged dry air mole fraction of carbon dioxide and methane (XCO_2 and XCH_4, hereafter GOSAT data) retrieved from the TANSO-FTS spectra could be influenced by aerosol and cirrus cloud particles.

To investigate their influences on the GOSAT data, we developed two-wavelength (532 and 1064 nm) polarization lidars and installed them at the Total Carbon Column Observing Network (TCCON) sites of Lauder (45S) in New Zealand, and Saga (33N) and Rikubetsu (44N) in Japan. Based on these lidar and TCCON observations, we found the influences of tropospheric particles on GOSAT XCO_2 data at Tsukuba and Saga.

These lidars also detected some increases in stratospheric aerosols by the volcanic eruptions of Sarychev Peak (48N) in June 2009, Puyehue-Cordón Caulle (41S) and Nabro (13N) in June 2011, and Calbuco (41S) in April 2015 after the launch of GOSAT. Increased stratospheric aerosols, especially the Calbuco particles, might impact on GOSAT data over Lauder.

Furthermore, we developed an improved two-wavelength polarization lidar for validation of GOSAT-2 which will be launched in 2018. The lidar also can measure water vapor profiles up to 5 km in nighttime using N_2 and H_2O Raman scattering. The lidar was installed at Burgos (19N) in Philippines with a new TCCON FTS in early 2017. We present the observational results of particles and their influences on the GOSAT data.

Validation of GOSAT Products in the Southern Hemisphere: Alice Springs Desert M-Gain Comparisons

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In addition to ongoing TCCON measurements, this past year we deployed a portable spectrometer system (Bruker EM-27/SUN) to Alice Springs in desert Australia in order to understand the differences in GOSAT M-gain and H-gain retrievals; M-gain retrievals are used over bright surfaces such as deserts and semi-arid regions. The world's deserts and semi-arid regions encompass large areas that are mostly undisturbed by anthropogenic emissions and are important for understanding the carbon cycle, however, there are no TCCON stations that are ideally located in a desert or semi-arid region that is not influenced by city emissions. Because of this, there has been no direct comparison and/or validation of GOSAT M-Gain retrievals with TCCON. Results from the measurement campaign in Alice Springs, Australia are shown here. A follow-up campaign with the EM27/SUN and an AirCore to provide vertically resolved profiles is planned in 2017.

An Introduction to a Carbon Verification System for TanSat

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The carbon verification system for TanSat consists of a retrieval system and methods for spatial interpolation, data fusion and data assimilation. The retrieval system incorporates a radiative transfer model and a retrieval algorithm (SCIATRAN) (Buchwitz et al., 1998).

The spatial interpolation provides effective means to construct a continuous surface from the discrete data by means of a method for high accuracy surface modeling (HASM) (Yue et al., 2016), which takes the limited retrieval data as its optimum control constraints and the mean value of all the retrieval XCO_2 as its driving field to estimate the reasonable spatial distribution of XCO_2 by filling missing data.

Data fusion is the process of integration of TanSat observation data and ground observation data into a consistent, accurate, and useful representation by using HASM, which takes the retrieval data as its driving field and the ground observation data as its optimum control constraints to improve the quality of the information so that it is more accurate than would be possible if the data sources were used individually.

Data assimilation is the process by which the ground observations and TanSat observations are incorporated into GEOS-Chem model by means of HASM in order to derive accurate estimates of the current and future states of the system, together with estimates of the uncertainty in the estimates. We use retrieval system to generate L2 products, spatial interpolation to produce L3 data, data fusion to improve accuracy of the interpolated L3 data, and data assimilation to get L4 products.

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4 Greenhouse Gas Observations for Emission Hot Spots and Flux Inversions on Regional and Global Scales

Remote sensing of volcanic CO_2, HF, HCl, SO_2, and BrO in the downwind plume of Mt. Etna

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Remote sensing of CO_2 enhancements in volcanic plumes can be a tool to estimate volcanic CO_2 emissions and thereby, to gain insight into the geological carbon cycle and into volcano interior processes. However, remote sensing of the volcanic CO_2 is challenged by the large atmospheric background concentrations masking the minute volcanic signal. Here, we report on a demonstrator study conducted in September 2015 at Mt. Etna on Sicily, where we deployed an EM27/SUN Fourier Transform Spectrometer together with a UV spectrometer on a ground-based, mobile platform. We successfully detected correlated intra-plume enhancements of CO_2 and volcanic SO_2, HF, HCl, and BrO. The path-integrated volcanic CO_2 enhancements amounted to about 0.5 ppm (on top of the ~400 ppm background). Figure 1 illustrates a successful remote detection of the volcanic plume in roughly 5-10 km distance from the source region.

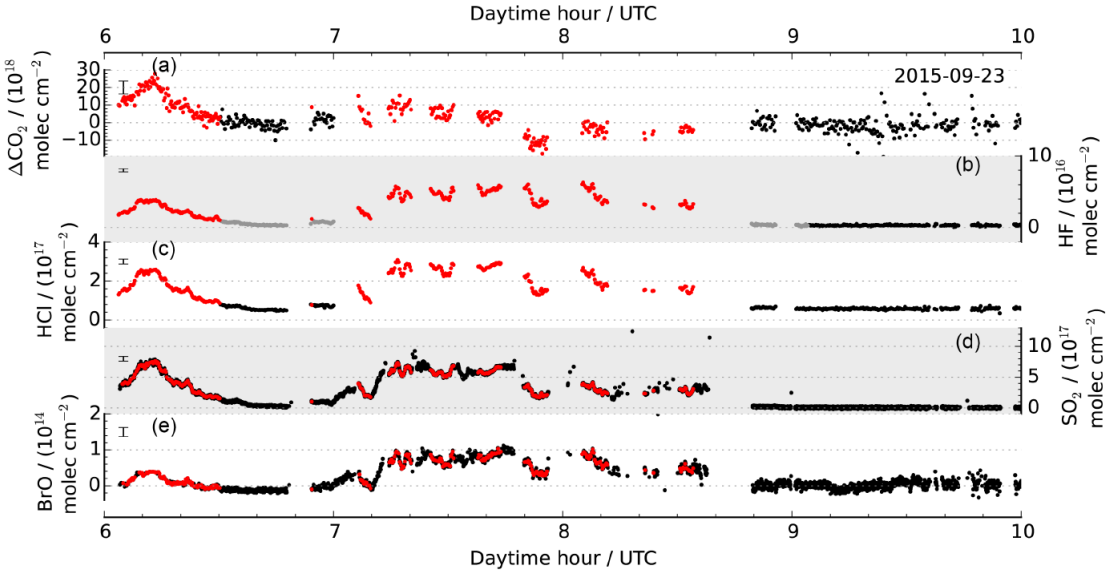

Figure 1. *Time series of volcanic vertical column enhancements in the plume of Mt. Etna observed on 21 September. CO_2 (first panel, left ordinate) correlates with enhancements in HF (second panel, right ordinate), HCl (third panel, left ordinate), SO_2 (fourth panel, right ordinate), and BrO (fifth subpanel, left ordinate). Grey symbols for HF indicate background measurements. Red closed symbols indicate intra-plume soundings. The precision estimated from the standard deviation of all background soundings is shown as an error bar in the upper left corner of each panel. Figure from Butz et al., 2017.*

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Were Tropical Land Ecosystems a Source of CO_2 in 2015? The View from OCO-2 and GOSAT.

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The lack of sufficient in situ observations in the tropics makes the carbon balance and seasonality for terrestrial regions such as the Amazon, the tropical rain forests in central Africa, and Tropical Asia poorly understood. In some years the budget is dominated by biomass burning, and in others the dominant factors seem to be GPP-driven. In recent years, a pattern is emerging in which satellite observations from GOSAT have led to persistent source terms for the tropics, while in situ constrained inversions tend toward neutral fluxes or even a tropical sink. In this presentation, we will present results from the OCO-2 model intercomparison project (OCO-2 MIP) that incorporates flux estimates using in situ data as well as OCO-2 and GOSAT retrievals from numerous independent models using different data assimilation schemes. The flux ensemble in Fig. 1 shows that OCO-2 induces striking agreement in estimates of both seasonality and budget for tropical regions in 2015 due to its unprecedented coverage. Further, these results show the same general results as GOSAT, namely that the Tropics are a source. We will also compare this result to independent data such as TCCON in an attempt to assess whether this estimate is overly impacted by satellite retrieval bias.

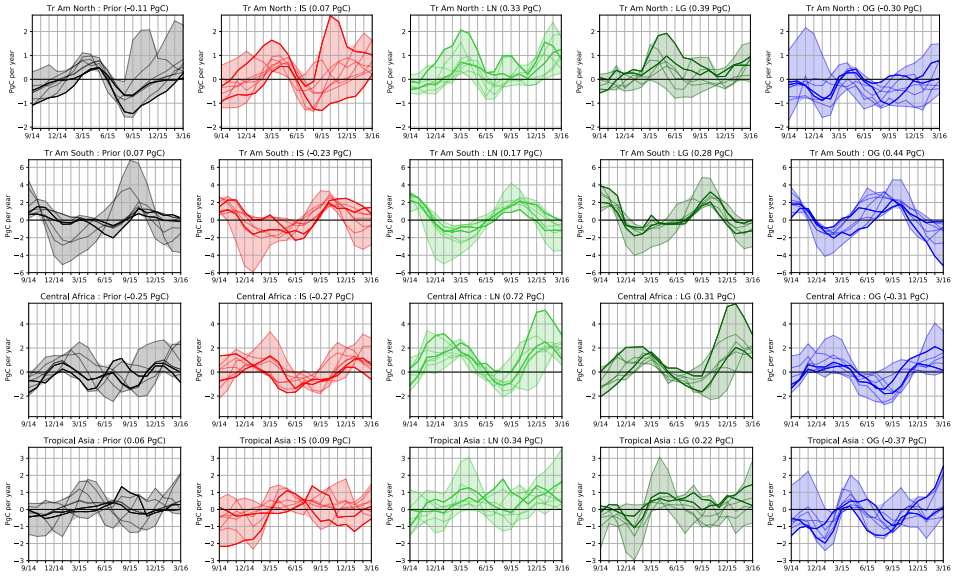

Figure 1 Prior (black) and Posterior total flux estimates from assimilating in situ (red), land nadir (light green), land glint (dark green) and ocean glint (blue) observations. Rows a)-d) depict the total flux time series for the a) western hemisphere tropics north of the equator, b) western hemisphere tropics south of the equator, c) Central Africa (between 15 S and 15 N in latitude, and d) Tropical Asia. The median annual flux for the two regions is in parentheses in the figure panel titles (e.g. a prior sink of 0.11 PgC for the western hemisphere tropics north of the equator).

Direct space-based observations of anthropogenic CO_2 emission areas from OCO-2

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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. This work provides the first direct observation of anthropogenic CO_2 from OCO-2 over the main pollution regions: eastern USA, central Europe, and East Asia. This is achieved by deseasonalizing and detrending OCO-2 CO_2 observations to derive CO_2 anomalies. Several small isolated emission areas (such as large cities) are detectable from the anomaly maps. The spatial distribution of the CO_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. The results of a cluster analysis confirm the spatial correlation between CO_2 and NO_2 data over areas with different amounts of pollution. We found positive correlation between CO_2 anomalies and emission inventories. The results demonstrate the power of spaceborne data for monitoring anthropogenic CO_2 emissions.

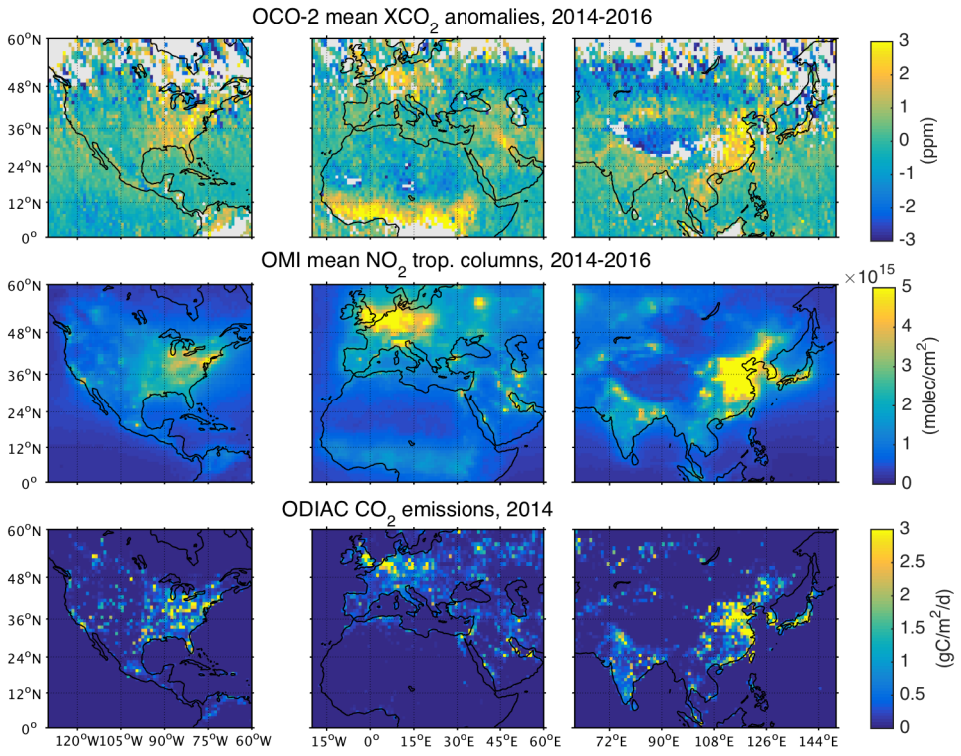

Figure 1: *(top row) Mean OCO-2 XCO_2 anomalies, for three different study areas. (middle row) Mean tropospheric OMI NO_2 columns. OCO-2 and OMI data are taken between September 2014 and April 2016. (bottom row) ODIAC emission inventory map from the year 2014. The spatial resolution is 1 × 1°.*

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Estimate of the SoCAB CO_2 flux using a Lagrangian-based method and TCCON and OCO-2 observations

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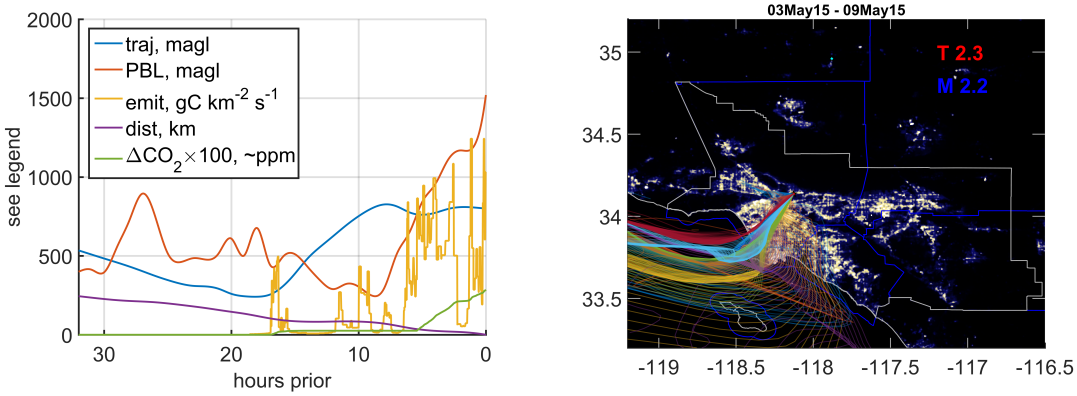
There have been extensive studies of California's South Coast Air Basin (SoCAB) CO_2 activity. These have included several remote sensing based studies (*Wunch et al.* 2009, *Kort et al.* 2012), and make the SoCAB a favorable test bed to quantify CO_2 emissions.

Estimating CO_2 fluxes from a large number (100+) of cities is a challenge. Ground-based networks are not scalable due to infrastructure requirements, and general circulation models are usually coarser than individual cities. Here, we present first steps towards creating a scalable flux inversion scheme by focusing on the SoCAB. We use satellite (OCO-2) observations and a Lagrangian-based inversion (Fig. 1), then use a Kalman filter to aggregate estimates.

Our flux estimates are biased high by $\sim$10% compared with bottom-up estimates. We perform several sensitivity tests and find several sources of error and bias. This includes a direct mapping of measurement bias to flux bias.



(a) Parameters of a single back trajectory plotted with time.

(b) Back trajectories over the SoCAB plotted over a nightlight map. Top right: TCCON and Model ΔX_{CO_2} estimates.

Figure 1: Visualization of Lagrangian trajectories used in the flux inversion.

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Monitoring anthropogenic CO_2 signatures using OCO-2 observations: an application to US power plants

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Carbon dioxide (CO_2) is the most significant anthropogenic greenhouse gas and it plays an important role in the Earth's radiative budget and climate. Anthropogenic CO_2 emissions from fossil fuel combustion have large impact on the atmospheric CO_2 spatio-temporal variability. Recently, measurements of column-averaged dry air mole fraction of CO_2 (XCO_2) have become available from the Orbiting Carbon Observatory-2 (OCO-2) (*Crisp et al.*, 2004). Based on such observations, *Hakkarainen et al.* (2016) derived XCO_2 anomaly maps and identified the major anthropogenic CO_2 emission areas over Europe, USA, and China.
In this work, we compare the distribution of the XCO_2 anomalies and various emission datasets in order to evaluate the contribution of different sectors. In particular, we analyse the spatial correlation between the XCO_2 anomalies and the EPA Greenhouse Gas Emissions Data from power plants over the United States (Fig.1). Furthermore, we compare the CO_2 anomalies with the distribution of other air pollutants, e.g. over large SO_2 emission sources (including power plants) as derived by *Fioletov et al.* (2016) using the observations from the Ozone Monitoring Instrument (OMI). Also, the contribution of the traditional emission sectors as provided by the EDGAR database is evaluated.

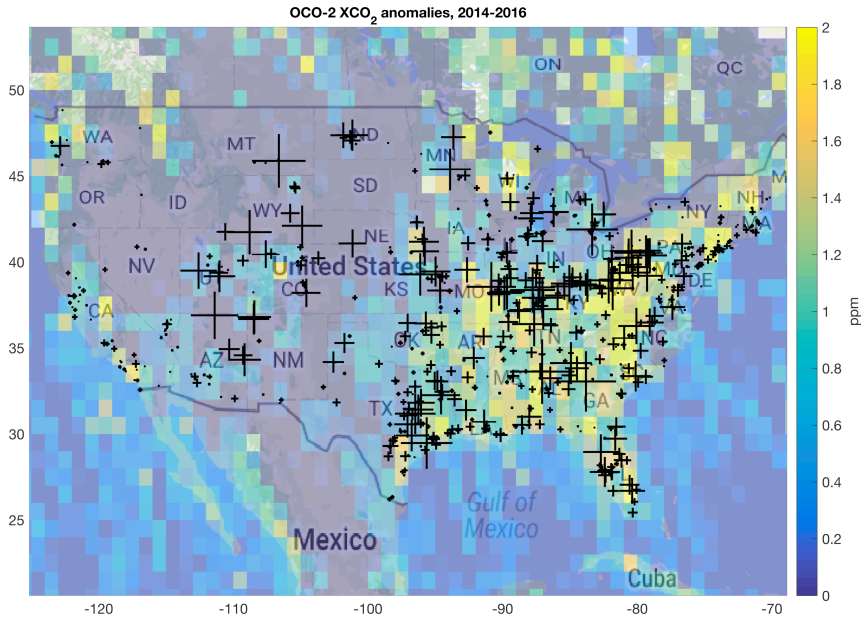

Figure 1: *EPA CO_2 emissions from US power plants overlapped to the OCO-2 XCO_2 anomalies. The size of the cross locating the emission source is proportional to the emission values for 2015.*

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Gross Primary Production (GPP) calculation component to estimate CO_2 emissions from Mega-cities using regional transport models

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Recent progress in satellite measurements of greenhouse gases enhances the inversion analysis of greenhouse gas emissions from mega-cities. We have conducted intensive observations with the GOSAT targeting mode operation over Kanto Plane, centered at Tokyo city. For analyzing data measured in both Short Wavelength InfraRed (SWIR) and thermal infraRed (TIR) bands, a Local ensemble transform Kalman filter/smoother (LETFK/KS) system has been developed based on a regional scale model, National Institute of Advanced Industrial Science and Technology Meso-scale Model (AIST-MM). However, as this model was originally developed to simulate transport of air pollutants, it has not been optimized to represent the effects of land-ecosystem. In this model, formulae for photosynthesis of vegetation and respiration of plants and soil are coded to be simply calculated based on the fixed parameters for each vegetation type, and it is not enough for precise calculation of emission and uptake of CO_2 by the ecosystem surrounding the target area. Although the atmospheric CO_2 concentrations calculated by AIST-MM fairly agree well observations for winter season, AIST-MM overestimate both respiration in night time and photosynthetic uptake of CO_2 during day time are overestimated for summer season. Therefore, it is necessary to develop a land ecosystem carbon balance model which can realistically simulate vegetation activities to be combined with AIST-MM. In this study, we have developed a gross primary production (GPP) calculation component as a part of the carbon balance model based on the algorithm of the "Biosphere model integrating Eco-physiological And Mechanistic approaches using Satellite data (BEAMS)" which can calculate GPP using satellite data explicitly representing daily variation of vegetation activities and diurnal variation of solar flux (Sasai, 2005; 2011). The fundamental inputs for the model is meteorological data, land cover type, Photosynthetically Active Radiation (PAR), the fraction of absorbed PAR (fPAR). As the meteorological data, GPV-MSM provided by Japan Meteorological Agency (JMA) is used, For the land cover type and fPAR, MODIS level-3 (MCD12Q1) and level-4 (MCD15A3H) are respectively used. PAR data provided by JAXA Satellite Monitoring for Environmental Studies (JASMES) are normalized referring the ground based measurements at Tsukuba site, and its scaling factor is applied to whole area. Then diurnal variation of PAR is calculated based on the solar zenith angle at each location. Spatial resolution of calculation is set to be 500 m based on the resolution of MODIS data, and temporal resolution is 1 hour referring the GPV-MSM data. GPP values calculated by the method are compared with ground based measurements provided by Forestry and Forest Products Research Institute (FFPRI) flux net. Comparison at "Yamashiro", "Fujiyoshida", and "Kawagoe" stations show that over estimation by the original component of AIST-MM is drastically improved, and annual amounts are agree well with measurements in about 20 %. As the comparison show that not only seasonal variation but also variation in a few days scale (synoptic scale) can be represented by the calculation, the component can be evaluated as having sufficient performance to be used in the regional scale models of which spatial and temporal resolution is very high. As the next step, we are developing a component to calculate the respirations of vegetation and soil with the same order of special and temporal resolutions as the GPP calculation.

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Quantifying regional fluxes of CO_2 using lower tropospheric partial columns of CO_2 retrieved from GOSAT measurements

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Space-based observations of column averaged carbon dioxide (CO_2) dry air mole fraction (XCO_2) provide significantly greater observation coverage than observations from the in situ observing network, and offer the prospect of better quantifying regional sources and sinks of CO_2. However, the space-based XCO_2 data vertically integrates the free tropospheric CO_2 signal with the boundary layer signal, weakening the influence of local sources and sinks on the observed CO_2 column. Recently available retrievals of CO_2 from measurements from the Greenhouse gases Observing SATellite (GOSAT) have tried to separate the retrieved CO_2 columns into lowermost tropospheric (LMT) and upper tropospheric (U) partial columns, so that the LMT partial columns would more strongly reflect the variability in local sources and sinks of CO_2. Here we use the GEOS-Chem four-dimensional variational (4D-Var) data assimilation system to assimilate the GOSAT LMT and U partial columns to assess the constraints that they provide on estimates of regional sources and sinks of CO_2. We evaluate the benefits of assimilating LMT and U partial columns compared to assimilating XCO_2 data alone. Previous studies have shown that the latitudinal distribution of CO_2 fluxes inferred in inversion analyses is influenced by the ability of the atmospheric models employed in the analyses to capture the vertical gradient in CO_2. Therefore, we also assess the information that the LMT and U data provide on the vertical gradient of CO_2 to help characterize discrepancies in vertical transport in the model.

Methane emissions from northern wetlands during soil freezing period estimated by atmospheric inversion modelling

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The northern wetland methane emissions continue throughout the autumn season, and the transition period when subsurface soil temperatures are near freezing may significantly contribute to the annual biospheric methane budget. Methane fluxes at northern latitudes were estimated with Carbon Tracker Europe – CH4 (CTE-CH4) atmospheric inversion model, optimizing separately for anthropogenic and biospheric fluxes. The results were combined with top-soil freeze data from satellite (SMOS) to quantify the late autumn season biospheric emissions and find out whether they continue throughout the period when the soil freezes. The enhanced in situ observation network at northern latitudes enables spatially better resolved flux estimates. Fluxes were solved in weekly time resolution, enabling the follow-up of soil freeze development. Generally, the methane emissions continued throughout the transition period until complete top-soil freeze, and there was a positive correlation between the magnitude of the emissions and the length of the transition period.

A study on regional emission events of greenhouse gases with GOSAT and OCO-2 for classification into anthropogenic and biogenic sources

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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 8 years since January 2009 with wide swath but sparse pointing. Orbiting Carbon Observatory-2 (OCO-2) has observed XCO_2 jointly on orbit since July 2014 with narrow swath but high resolution.

We use two retrieved datasets as GOSAT observation data. One is ACOS GOSAT/TANSO-FTS Level 2 Standard Product B7.3 by NASA/JPL, and the other is NIES TANSO-FTS SWIR L2 Product V02. As OCO-2 observation data, OCO-2 Operational L2 Data Version 7 is used. By comparing among these datasets, the biases and temporal variability of greenhouse gases are clarified. The GOSAT conducts strategic target observations frequently as well as grid pattern observations every 3 days over megacities and possible emission sources. The OCO-2 is operated with a 16-day (233-revolution) repeat cycle, thus there also exist finer-resolved observations over megacities. In this study, it is aimed to detect emission events on a regional scale such as megacities.

Time series data of XCO_2 and XCH_4 are obtained from satellite observation datasets, and functions which express typical inter-annual and seasonal variation are fitted to each study area. Consequently, anomalous events of XCO_2 and XCH_4 are extracted by the difference between each time series dataset and the fitted function. Additionally, Open source Data Inventory of Anthropogenic CO_2 emission (ODIAC) is used in this study as an inventory of anthropogenic CO_2 emissions. Correlational analyses between detrended XCO_2 and XCH_4 by satellite observations and anthropogenic emissions are also carried out to classify the cause of regional emission events into anthropogenic and biogenic sources.

The contribution of large urban areas to enhancements in local CO_2 concentrations based on OCO-2 observations

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Unprecedentedly extensive urbanization in 21st century is currently responsible for nearly 70% of CO_2 emissions worldwide. By the beginning of the present decade the global urban population has surpassed the rural population by amount for the first time in history marking the oncoming century of extensive urbanization. CO_2 concentration meanwhile has experienced unprecedented increase over last 50 years (from around 320 to nearly 400 ppm) becoming the most important long-live greenhouse gas in the world. Nowadays global urban areas became responsible for nearly 70% of global CO_2 emissions worldwide. Previous studies have shown how challenging is to quantify CO_2 anomalies over urban areas mainly due to difficulties of urban area delineation and to limitations of modern CO_2 measuring techniques at urban scales. Most of previous studies addressed to inventory-based statistics either for greenhouse gas emission quantification or to urban areas delineation. In our study we address solely to high-resolution remote sensing datasets to solve both delineation and CO_2 quantification issues for large urban areas. Therefore, we determine the boundaries of each urban area based on The Defense Meteorological Satellite Program-Operational Linescan System (DMSP-OLS) datasets. To quantify CO_2 anomalies we address to very high resolution satellite instrument OCO-2 (Orbiting Carbon Observatory) supported by datasets from other carbon measuring satellites. The use of these instruments in conjugation allows to estimate CO_2 anomalies in the most populated (more than 2 million population) and the largest urban areas (more than 500 km^2) worldwide with very high resolution. As a result we provide CO_2 urban anomalies to determine which cities are responsible for the strongest enhancements of local emissions in comparison with background CO_2 values.

Regional atmospheric greenhouse gas distributions observed during ACT-America field campaigns

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Uncertainties in greenhouse gas (GHG) sources and sinks limit our ability to make accurate forecasts of global climate changes, while uncertainty in atmospheric transport restrains our ability to infer GHG sources and sinks from long-term GHG observational networks since these networks are too sparse to deconvolve uncertainties in fluxes and transport together. The Atmospheric Carbon and Transport (ACT) - America mission aims to improve our understanding of GHG transports and fluxes through intensive airborne observations of GHG sources, sinks, and transport within midlatitude weather systems.

The first two ACT-America field campaigns were conducted in summer 2016 and winter 2017. Remote and in situ data were collected with two aircraft across cold and warm fronts associated with low pressure systems and around high pressure ridges during fair weather conditions in three eastern US regions (Mid-Atlantic; Mid-West; South). The observed distributions of GHGs, especially CO_2 and CH_4, within frontal systems and during fair weather are shown, and comparisons of summer and winter atmospheric carbon distributions across different weather systems are discussed. We also present observations of CO_2 and CH_4 changes within the atmospheric boundary layer, which can lead to improved understanding of GHG exchanges between the atmosphere and land surfaces.

Initial analysis indicates that very smooth CO_2 distributions in free troposphere were common in eastern US, while spatial variability of planetary boundary layer CO_2 could be very large, reaching ~ 40 ppm on a scale ~500 km, especially when crossing frontal systems. For column CO_2 (XCO_2) averaged over lowest ~6 km of the troposphere, the variability on the same spatial scale observed by airborne CO_2 lidar was significant too and could be as high as about ~10 ppm. Also, a large CO_2 drawdown signal of at least 15 ppm was observed in the planetary boundary layer compared to the free troposphere during the summer flight campaign in the Mid-West. In contrast, for the same region during the winter campaign, 10 ppm or higher CO_2 values were found in the boundary layer compared to that of the free troposphere due to a combination of anthropogenic emissions and limited biogenic respiration along with minimal CO_2 uptake by vegetation and less vertical mixing of the troposphere in cold weather. Future work will focus on upcoming field campaigns and the application of our observations to model comparisons to improve transport uncertainties and GHG flux estimates. These results will ultimately be used to improve our understanding of global GHG distributions and improve climate forecasts.

The potential of satellite-measured XCO_2 to evaluate land surface models

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Constraining the sources and sinks of atmospheric CO_2 continues to be the ultimate goal of space-based CO_2 measurements. GOSAT and OCO-2 provide column-averaged dry air mole fractions of CO_2 (XCO_2) that can be assimilated into CO_2 inversion systems to infer regional CO_2 fluxes. However, this approach is sensitive to several factors, including residual regional-scale biases in the observations that may induce false fluxes and also potential error sources within the model inversion system (e.g., in the transport model, inversion setup, or prior flux components). In this poster, we present a parallel research approach where we compare satellite-measured XCO_2 regionally to XCO_2 fields from models that assimilate in-situ measurements. We concentrate especially on a quantitative analysis of the GOSAT ACOS XCO_2 seasonal cycle which has recently been evaluated against ground-based XCO_2 retrievals at 16 different TCCON sites by *Lindqvist et al.* (2015). Our preliminary results show that the XCO_2 seasonal cycle amplitude from GOSAT observations generally agrees with models (to within about 1 ppm) in regions where the models are well constrained by in-situ measurements. However, we identify several regions where the seasonal cycle amplitudes differ by up to about 3 ppm or are out of phase. As these differences are larger than previously evaluated errors in GOSAT observations, we explore the underlying reasons for these discrepancies by comparing model fluxes in these regions. We find a connection between a too shallow XCO_2 seasonal cycle amplitude and a low variability in the net ecosystem exchange related to the prior biospheric fluxes at subtropical grasslands or seasonally dry forests. In these particular regions, in situ measurements of CO_2 are scarce, so the models are less constrained by measurements and thus may give more weight to their prior flux constraints, which for the biospheric fluxes are provided by their land surface models. We also evaluate the effect of transport on the seasonal cycle amplitude through specific experiments and by addressing transport model differences. The results of this study provide example guidance to what extent satellite-retrieved XCO_2 can directly be used to evaluate differences between inverse models and to learn about land surface models.

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Responses of tropical terrestrial biosphere carbon cycle to the 2015-2016 El Niño

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The 2015-2016 El Niño, the 2nd strongest since the 1950s, led to historic high temperature and low precipitation over the tropics while the atmospheric CO_2 growth rate was the largest on record. The launch of the Orbiting Carbon Observatory-2 (OCO-2) shortly before the 2015-2016 El Niño event provides an opportunity to understand how tropical land carbon fluxes respond to the warm and dry climate characteristics of the El Niño conditions. The El Niño events may also provide a natural experiment to study the response of tropical land carbon fluxes to future climate, since anomalously warm and dry tropical environments typical of El Niño are expected to be more frequent under most emission scenarios. Here we quantified the response of net biosphere exchange (NBE) and biomass burning to these climate anomalies by assimilating column CO_2 from Greenhouse Gases Observing Satellite (GOSAT) and Orbiting Carbon Observatory-2, and CO from Measurements of Pollution in the Troposphere (MOPITT) into an atmospheric inversion framework. We further quantified Gross Primary Production with the Solar Induced Fluorescence (SIF) from GOSAT, and calculated the respiration as a residual term. We quantified the impact of 2015-2016 El Niño in the context of tropical biosphere flux interannual variability constrained by GOSAT and OCO-2, and discussed the time-evolution of the 2015-2016 El Niño impact on tropical biosphere carbon flux anomaly. Relative to the 2011 La Niña, the pantropical biosphere released 2.4 ± 0.34 Gt more carbon into the atmosphere in 2015, with an approximately equal distribution over three tropical continents. However, the dominant processes were different: GPP reduced (0.9 ± 0.97 GtC) in tropical South America, fire increased (0.4 ± 0.10 GtC) in tropical Asia, and respiration increased (0.6 ± 1.01 GtC) in Africa. Our results imply a positive carbon-climate feedback if the frequency of El Niño-like climate anomaly increase in the future.

Observing System Experiments with Multiple Satellites for CO2 Analysis using the LETKF

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Impacts of CO2 concentration data obtained from multiple satellite measurements from GOSAT and OCO-2 on the estimation of global surface CO2 fluxes have been investigated using an ensemble-based four-dimensional data assimilation system based on the LETKF.

An online atmospheric transport model (MJ98-CDTM) is employed in the data assimilation system to optimize surface CO2 fluxes from real observations at spatial and temporal resolutions of 6 days and 2.8°, respectively. We used GOSAT L2 Ver. 2.X and OCO-2 L2 Ver. 7r in our observing system experiments (OSEs). We estimated and corrected the satellite observation bias using an independent CO2 concentration analysis based on a Bayesian synthesis inversion (JMA-CO2) adopted in TransCom 3. We have tested 4 types of satellite bias correction experiments (w/o bias correction (RAW), monthly mean bias correction (MON), all data bias correction (ALL) and globally constant bias correction (FIX)) using JMA CO2 in our data assimilation system to avoid inconsistency of satellite data.

Our results showed that estimated CO2 concentration and fluxes are significantly sensitive to the bias correction scheme. The MON experiments show the smallest mismatch between the JMA CO2 and assimilated CO2 concentrations. In the preliminary results, the mismatch between multiple satellite assimilation (GOSAT and OCO-2) and single satellite assimilation (GOSAT or OCO-2) against JMA-CO2 is almost identical.

In conclusion, we should have a reasonable satellite bias correction scheme in CO2 data assimilation. By usimg satellite data, we could obtain realistic CO2 concentration field and modifying surface CO2 flux over almost entire land surface by our satellite bias correction scheme. We confirmed that this satellite bias correction scheme makes it possible to use multiple satellite observation data simultaneously in CO2 data assimilation.

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Interannual variability of the surface carbon dioxide and methane fluxes inferred from GOSAT observations.

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GOSAT Level 4 products provide inverse model estimates of the surface CO_2 and CH_4 fluxes based on ground-based and GOSAT observations. The fluxes are estimated as regional corrections to prior fluxes using a Kalman smoother technique applied over short 3 months (for CO_2) or 4 months (for CH_4) time window. Control state includes 64 regions (42 land and 22 ocean) for CO_2 and 43 regions (42 land and 1 ocean, each region has 3 categories: anthropogenic, biogenic and fire) for CH_4. The inter-annually varying fluxes available for period of 2009-2013 reflect impact by climate variability on net ecosystem CO_2 exchange and methane emissions.

We found that GOSAT data are most useful for understanding the extent of changes in the surface fluxes in remote regions, such as Africa, South America and Siberia. We demonstrated a high degree of correlation between regional CO_2 fluxes and temperature, precipitation and NDVI for South America and Africa, that is related to known see-saw precipitation pattern with negative correlation of the precipitation between Amazon and Congo basins.

Methane flux estimates over Amazonia in 2011 made with inverse model using GOSAT observations are showing stronger emissions inferred when GOSAT data is included in the inversion.

Another case of high correlation between GOSAT-based surface CO_2 flux estimates and climate indices was observed during blocking event that led to wide-spread forest fires over Russia in 2010. A higher spatial- and temporal-resolution transport modeling was applied for North Eurasian flux variability study, based on coupled NIES TM-Flexpart transport model. Clearly better correlation was achieved while using both GOSAT and ground based data, as compared to using the ground-based data alone.

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Nested regional CO_2 inversions over Europe using OCO-2 and GOSAT measurements

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Lagrangian particle dispersion models (LPDMs) allow for the resolution of flux signals at scales not possible with current global Eulerian-based inversion schemes, but the sensitivity to boundary conditions for long-lived tracers such as greenhouse gases makes their application difficult. To that end, a two-step nested inversion system has been developed, wherein a higher-resolution Lagrangian model is nested without a coarser resolution global model, with the two linked through their observation vector. The theorertical basis was laid out in Rödenbeck et al. (2009) and has been implemented for surface-based measurements over the European domain in Trusilova et al. (2010) and Kountouris et al. (2016). The current study applies the method to both surface-based measurements and spaceborne total-column measurements of CO_2, making use of retrievals from both GOSAT and OCO-2. The mesoscale transport is resolved up to 0.25 degree spatial resolution, and sensitivity tests using higher resolution (6 km) are included. Results for 2015 and 2016 are presented. The potential applicability of this sort of inversion approach to future "imager-type" (high resolution broad swath) satellite-based measurements of CO_2 or CH_4 is discussed, as the computational effeciency of Lagrangian modelling decreases with the density of measurements.

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Key opportunities and challenges in using space-based observations for greenhouse gas flux estimation at regional to global scales

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Space-based observations of greenhouse gases have created a host of opportunities for furthering our understanding of the global carbon cycle. While logistical and practical challenges have thus far limited the spatial and temporal density of in situ observational networks, space-based observations, at least in principle, offer the possibility of global and frequent observations of the atmosphere. Delivering on the promises of space-based observations is challenging, however.

Instrument design, delivery to orbit, and the development of retrieval algorithms pose great challenges, as discussed throughout this workshop. Even once estimates of concentrations of atmospheric constituents are available, however, their use for furthering our understanding of carbon emissions and uptake presents unique challenges.

Focusing primarily on CO2, this talk will discuss both the opportunities and challenges associated with using space-based observations for constraining surface fluxes. Satellite-based observations are fundamentally different from in situ observations in terms of the number of measurements, their sensitivity to surface fluxes, the timescales over which information is carried downwind, and the statistical properties (including biases and correlations) associated with their uncertainties. These have fundamental implications for the types of questions that are best addressed by space-based observations, and also for the design of inversion and data assimilation systems that can best take advantage of the information content of these data. Successfully addressing the unique challenges of satellite observations, however, will make it possible to fully leverage the complementary nature of in situ and space-based observations of greenhouse gases.

The ideas described above will be illustrated through the lens of recent and ongoing studies utilizing data from both existing (e.g., GOSAT, OCO-2) and proposed (e.g., ASCENDS) missions.

Quantifying CO_2 emissions from individual coal power plants using OCO-2 observations

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We present estimates of CO_2 emissions from individual coal power plants based on OCO-2 observations. Our approach was inspired by studies for CarbonSat, a mission proposed to ESA to quantify emissions at multiple scales, including individual facilities such as mid- to large-sized coal power plants. Their proposed approach involved acquiring accurate and precise high spatial resolution CO_2 imaging observations over emission plumes. Although OCO-2 has a much narrower swath than proposed for CarbonSat, we show that OCO-2's limited imaging capability can be used to quantify CO_2 emissions from individual coal power plants, in some select cases. After locating OCO-2 overpasses and close flybys of power plants of interest, we run a 2D Gaussian plume model with the best available reported emission values to determine a priori CO_2 enhancements. We then define a background from elsewhere in the OCO-2 swath to convert enhancements to XCO_2, fit the model XCO_2 to the OCO-2 observations with a least squares fit, and derive a posteriori emission estimates as well as associated uncertainties. We first demonstrate the method on US coal power plants which have detailed hourly emission data available from the Environmental Protection Agency (EPA), then we apply the method to international power plants where available CO_2 emission data have larger uncertainties. Based on these new results, we will briefly discuss how our ability to estimate facility CO_2 emissions might change with upcoming and proposed satellite missions and what a desired future constellation for anthropogenic CO_2 monitoring might look like.

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Monitoring carbon cycle change using an integrated observation, modeling and analysis system

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We conducted a three-year research project toward developing an integrated carbon observation and analysis system based on satellite, airborne and ground-based observations, and atmospheric and terrestrial carbon cycle models. Aircraft observations of atmospheric greenhouse gases (GHGs) were strengthened based on the “Comprehensive Observation Network for TRace gases by AIrLiner (CONTRAIL)” project. Atmospheric transport modeling, inverse modeling, and assimilation methods have also been developed and improved for better utilization of observational data from the Asia-Pacific region. Global and regional surface fluxes were estimated by both "top-down” approach using inverse models and "bottom-up” approach using surface flux observation network data and upscaling with either empirical models or terrestrial ecosystem models.

The main progresses have been the better constraints of global, continental and regional carbon budgets, and detection of terrestrial carbon cycle change particularly in the Asia-Pacific region.
1) Multiple approaches including different types of top-down models and bottom-up upscaling techniques contributed to designate uncertainties in the estimates of large emissions (e.g. fuel use and land use changes).
2) Key target regions and events were indicated as potential hot-spots in the Asia-Pacific where we need further targeted research. (e.g. potential increase in terrestrial carbon sink in Siberia and East Asia, uncertainty in the recent rapid growth of anthropogenic GHG emissions in East Asia, emissions from land use change and El Niño-induced extreme forest fires in Southeast Asia)
3) A prototype system was developed and tested for future operational monitoring of changes in regional, continental, and global GHGs budgets based on integration of observation and modeling.

We also discuss remaining issues and the way to solve them in the next steps (e.g. strategies of intensive observations in targeted area, a platform for multi-model ensemble, and utilization of satellite-based total column observations)

Characterizing atmospheric transport errors in models using GOSAT XCH_4 retrievals

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Space-based retrievals of column-averaged dry-air mole fractions of CH_4 (XCH_4), together with chemistry transport models (CTMs), are being used to infer CH_4 surface emissions. In these inverse modeling analyses, the estimates of the CH_4 surface emissions strongly depend on the fidelity of the atmospheric transport models. However, it is challenging to characterize errors in these atmospheric models. Here we use GOSAT XCH_4 retrievals and the GEOS-Chem global CTM, at a horizontal resolution of 4°x5°, to show that space-based XCH_4 observations can provide some constraints on model errors. We use a weak constraint four dimensional variational (4D-Var) data assimilation method to identify and partially mitigate the impact of model biases (including transport bias) on the global CH_4 distribution. The sensitivity of the observations to different types of model errors is investigated in a set of Observing System Simulation Experiments (OSSEs), where we show that satellite XCH_4 retrievals can provide some information on the vertical distribution of model errors. For example, assimilation of the XCH_4 observations can mitigate some of the bias in CH_4 in the GEOS-Chem stratosphere at high latitudes. More generally, the weak constraint 4D-Var assimilation of XCH_4 reveals that the vertical transport over major source regions (such as China) is too weak and will adversely impact inferred CH_4 source estimates. Our work shows that although the vertical information in the XCH_4 retrievals is limited, there is sufficient information to partially mitigate some of the model errors in the context of the weak constraint 4D-Var assimilation approach.

Towards assimilation of XCH_4 GOSAT observations to global CH_4 emission estimates by CTE-CH_4 data assimilation system

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Atmospheric 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 (*Heimann* 2011), but large uncertainty still remains in model estimates, and further understanding is needed for source attribution. Here we estimate global CH_4 emissions for the 21st century by CTE-CH_4 data assimilation system to better understand causes of increased atmospheric CH_4 since 2007. In *Tsuruta et al.* (2017), we estimated global anthropogenic and biospheric emissions simultaneously, constrained by surface in-situ atmospheric CH_4 observations. However, our emission estimates in the tropics and extratropics were not well optimised due to the sparse observation network. In addition, the evaluation of simulated posterior total column-averaged CH_4 from CTE-CH_4 against GOSAT and TCCON retrievals showed latitudinal bias of up to $\sim$23 ppb, which was larger in the Southern Hemisphere than in the Northern Hemisphere. The large model bias was found in the Southern Hemisphere partly because emission estimates were not well optimised in the tropics and extra tropics. To improve the model estimates, we will assimilate GOSAT retrievals of column-averaged CH_4 in addition to surface in-situ atmospheric CH_4 observations, taking advantage of spatial and temporal coverage of the additional observations. Not only the emissions, but also atmospheric transport caused the part of the latitudinal bias, which will be taken into account in the new inversion. The model estimates will be evaluated against surface in-situ CH_4 observations and retrievals of column-averaged CH_4 from TCCON.

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Chinese CO2 fluxes inferred from OCO-2 and GOSAT and from in situ data during the 2015 El Niño event

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China represents a significant contribution to global observed variations of atmospheric carbon dioxide (CO2) by virtue of its large land area and substantial changes in the use of this land, and its high fossil fuel emissions. We report CO2 fluxes in 2014 and 2015 inferred, using an ensemble Kalman Filter [Feng et al, 2009], from data collected from five new ground-based sites over China (together with available NOAA sites) with fluxes inferred from OCO-2 (version 7) and GOSAT (UoL v7) XCO2 data. We find that posterior CO2 fluxes are generally consistent with independent validation data downwind of the Chinese mainland. To better understand the response of the Chinese biosphere to the 2015 El Niño we compare the magnitude and distribution of CO2 fluxes inferred from different data. We find that CO2 fluxes inferred from OCO-2 and GOSAT are higher (lower) than those inferred from the in situ data in 2014 (2015).

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Disentangling GEOS model biases from those of retrieved column carbon dioxide

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The goal of carbon dioxide (CO2) flux inversions is to correct persistent, spatially coherent model errors (i.e., biases) caused by inaccuracies in surface sources and sinks. By design, if the inverted data also have spatially coherent biases, the inversion will alias the data biases into the inferred fluxes. While present-day satellite retrievals of column CO2 have global mean biases of less than a ppm, their regional impact on flux inversions remains significant. This work develops a parameterized climatology of biases in the predicted CO2 mixing ratios throughout the atmosphere from the Goddard Earth Observing System (GEOS) general circulation model. The model bias climatology is represented using a linear combination of an ensemble of tracers that separate uncertainty from different transport processes and surface flux components, and its coefficients are optimized to fit an extensive suite of evaluation data from surface sites, aircraft profiles, and the Total Carbon Column Observing Network (TCCON). Estimates of the accuracy of the bias climatology follow from withholding individual years from the evaluation data and comparing the fit to the whithheld year. After removing the parameterized biases from the model, the remaining model-data mismatches may be attributed to retrieval bias. As a final evaluation, the resulting estimates of model and retrieval biases are compared to further independent data and evaluated against the current scientific understanding of retrieval biases.

Monitoring Anthropogenic CO_2 Emissions by the Seasonal Changes of Atmospheric Xco_2 from Satellite Observations

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Anthropogenic carbon dioxide (CO_2) emission is the dominant driving factor for the increasing CO_2 concentration in the atmosphere. Satellites observation for CO_2 concentration has been shown to be one of the most promising and effective method to monitor and evaluate anthropogenic CO_2 emissions. In this study, we use the column-averaged CO_2 dry-air mole fraction (Xco_2) data from the Greenhouse gases Observation SATellite (GOSAT) and derive the Xco_2 excess due to anthropogenic emission by subtracting background concentration of atmospheric CO_2 and the terrestrial biospheric contribution. The Xco_2 excess data are then compared with anthropogenic emissions from ODIAC data to investigate the relationship between temporal variations and Xco_2 excess and the underlying anthropogenic CO_2 emissions.
Firstly, k-means cluster analysis are used to divide the Xco_2 excess data into 15 clusters according to their temporally changing features. These clusters represent 15 types of distinct seasonal changing patterns of Xco_2 excess. Secondly, in order to estimate anthropogenic CO_2 emissions, we further implement multiple regression on bottom-up emissions, which are provided by the Chinese Academy for Environmental Planning (CAEP) with high-resolution of 0.1° in 2012 over China、NDVI from GOSAT and Xco_2 excess data from each cluster to quantify the degree of variations in emissions can be explained by the variations of Xco_2 excess from GOSAT. Finally, by comparing estimated anthropogenic CO_2 emissions with ODIAC anthropogenic emission dataset, we discuss the potential of monitoring anthropogenic CO_2 emissions by the seasonal changes of atmospheric CO_2 concentration from satellite observations.

Keywords: GOSAT, carbon dioxide, Anthropogenic Emissions, temporal variation of Xco_2

The joint methane retrieval from GOSAT SWIR and TIR spectra over Western Siberia

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Methane distribution in the Earth's atmosphere and its main sources and sinks localization are very important for climate change studies. Satellite measurements are one of the most effective approaches for monitoring the global distributions of greenhouse gases with high spatial and temporal resolution, as well as localization of its main sources and sinks. The modern spacecraft generation GOSAT/GOSAT-2 satellites with high resolution TANSO spectrometers on board are capable to carry out continuous measurements of outgoing radiation in thermal infrared (TIR) and short wavelength infrared (SWIR) spectral bands.

We developed and implemented into software package the joint methane vertical profiles retrieval with optimal estimation method from GOSAT SWIR and TIR spectra measured simultaneously. The modified software package FIRE-ARMS (*Gribanov et al.* (2001)) with embedded VLIDORT (*Spurr* (2006)) procedures was used as a forward model for spectra and Jacobian calculation in both TIR and SWIR bands using the same atmospheric model with the same vertical layering. The other additional procedures added to extract data from HDF5-files, select spectra at cloudless conditions and build initial guess atmosphere model from NCEP/NCAR or ECMWF/ERA-Interim reanalysis data. The data of HIPPO experiment aircraft observations (*Wofsy* (2011)) together with MACC reanalysis (*Massart et al.* (2014)) data were used for covariance matrices modeling. Results obtained from observations made in summer of 2016 over Western Siberia together with retrieval characterization in terms of a posterioiri covariance matrices and averaging kernels are discussed.

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5 Global Observations of Greenhouse Gases for Process Studies and Interactions of Carbon Cycle and Climate

Atmospheric CO_2 constraints on tropical carbon cycle processes

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Process understanding of the tropical carbon (C) budget is limited by uncertainty on the fundamental controls regulating terrestrial C cycling. Here we use the Carbon Monitoring System Flux (CMS-Flux) atmospheric CO_2 data assimilation framework, combined with the CARbon DAta-MOdel fraMework terrestrial C cycle analysis (CARDAMOM) to quantitatively constrain process controls on the seasonal and inter-annual tropical C balance. The combined CMS-Flux and CARDAMOM data-assimilation analyses provide a novel methodology for combining satellite-derived atmospheric C datasets (GOSAT CO_2 and MOPPITT CO) and land-surface datasets (MODIS LAI, GLAS-derived biomass, GOSAT fluorescence retrievals) in a common terrestrial C cycle synthesis. Comparisons between land-surface and atmospheric CO_2 constrained C fluxes between 2010-2011 over critical tropical ecosystems – including the Amazon river basin, Indonesian Archipelago and across the Northern African dry tropics – reveal significant and substantial seasonal and inter-annual discrepancies in the amplitude and timing of CO_2 tropical CO2 fluxes (50 – 400 Tg C/month). We find that improved constraints on water stress on C uptake and heterotrophic respiration temperature dependence explain discrepancies in seasonal-to-inter-annual CO_2 flux variability. Finally, we show that satellite-based atmospheric CO_2 constraints on carbon-water interactions are critical for predicting the pan-tropical C response in 2012, based on CO_2 data assimilated during 2010-2011.

RemoTeC GOSAT retrievals and the 2011 La Nina: Terrestrial CO2 flux variations over the Southern Hemisphere

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We report on the latest RemoTeC GOSAT products for XCO2 and XCH4. Our GOSAT processing consists of two main components, a near-real time operational product (XCH4 PROXY) for the CAMS project and a full mission (2009-2015) product (XCO2 and XCH4) for the ESA GHG-CCI project. An overview of both products including quality assessment and validation of the data products will be shown.
Building upon the work on the Carbon sink in Australia (*Detmers et al.* 2015) we present the first results of our study on terrestrial CO2 flux variations in the Southern Hemisphere. This study extends the GOSAT inversions to other semi-arid regions in the Southern Hemisphere during the 2011 La Nina and compares the results to three different terrestrial biosphere models (LPJ, CASA-GFED4 and ORCHIDEE).
The results show significant differences in the inter-annual variation (IAV) of CO2 uptake between the models and highlight the role that GOSAT XCO2 observations can play in improving our understanding of the global carbon cycle.

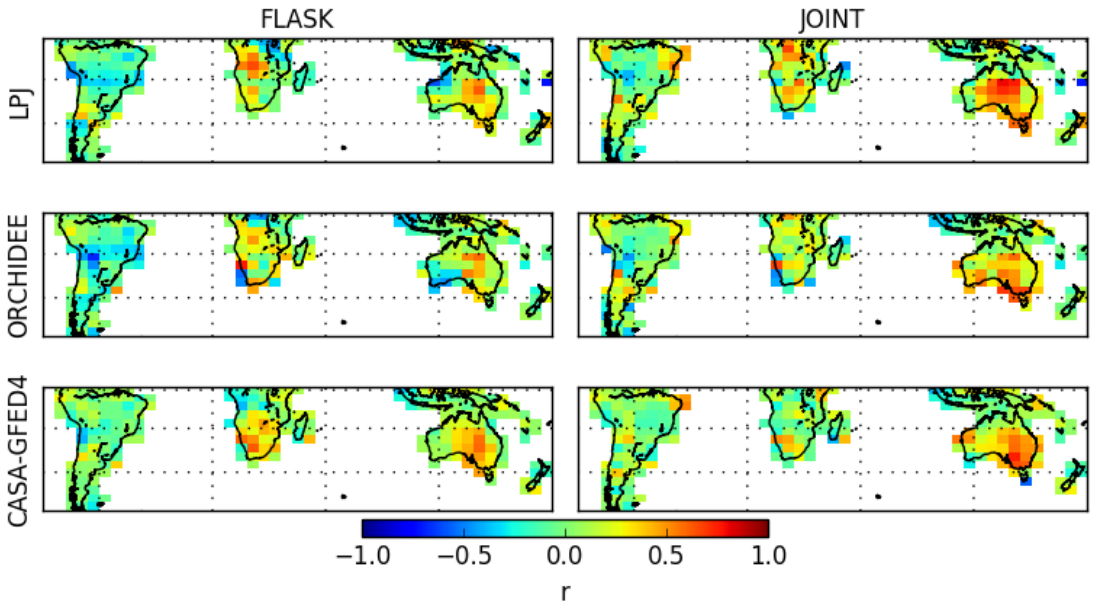

Figure 1: *Spatial patterns of the Pierson correlation coefficients (r) between the IAV of CO2 fluxes derived from GOSAT and the different terrestrial models.*

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Investigating Biosphere-Atmosphere Interactions using XCO2 and MODIS vegetation parameters: A comparison study of GOSAT retrievals and model simulations

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Using measurements of the column-averaged CO_2 dry air mole fraction (XCO_2) from GOSAT, model simulations of XCO_2 from CarbonTrack, and normalized difference vegetation index (NDVI) and land surface temperature (LST) from MODIS, this study proposes a data-driven approach to assess the consistency of XCO_2 from satellite retrievals and model simulations in characterizing the biosphere-atmosphere interactions. A unique global land mapping dataset of XCO_2 with a resolution of 1° by 1° in space, and three days in time, from June 2009 to May 2016, which facilitates the assessment at a fine scale, is completely produced from GOSAT XCO_2 retrievals. We then conduct a statistical fitting method to obtain the time series characteristics including seasonal cycle amplitudes (SCA) and phase of XCO_2 and NDVI, and implement correlation analyses of seasonal variation between XCO_2 and the vegetation parameters. As a result, the spatial distribution of XCO_2 SCA from GOSAT and CarbonTracker decrease with latitude from north to south, which is in good agreement with each other. The spatial pattern of XCO_2 SCA corresponds well to the vegetation seasonal activity revealed by NDVI, with a strong correlation coefficient more than 0.70 in the northern hemisphere (NH). Some hotpots with different SCA, phase or correlation between XCO_2 and NDVI or LST in the subtropical areas, including Northern India, Central Africa and Southern China, and high latitude, including Western Europe and Western America, shown between satellite retrievals and model simulations, demonstrate the deficiency exist in model simulations or satellite retrievals. Results from this study provide reference for better improving the model process and satellite inversion, and importing remote sensing data in assessing atmospheric CO_2 columns measurements.

Keywords: GOSAT; CarbonTracker; XCO_2; Consistency Assessment; MODIS

Quantifying regional biogeochemical budgets: the scientific challenges

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Our scientific understanding of the global budgets of the major long-lived biogeochemical greenhouse gases is still far from complete and there are several key open questions. Important examples include the Arctic budgets of carbon dioxide and methane, the terrestrial sink for carbon dioxide, its climate sensitivity, anthropogenic impacts on land by changes in land use and management and longer term variations of CO2 uptake in key ocean areas. Quantifying regional budgets and how they vary in time and space provides important clues on the underlying mechanisms and drivers. This information is thus highly useful for the scientific understanding of the Earth System as well as for societal needs. However the relevant atmospheric signals are very small and require a high accuracy for a robust detection. Comprehensive global data assimilation systems, which can ingest the multitude of different biogeochemical data streams (space borne, in situ, surface flux measurements, anthropogenic drivers, etc) in addition to the classical parameters for the physical atmosphere-ocean-land surface environment, offer a promising approach. However, the development of such systems is difficult: in part due to the vastly different temporal and spatial scales covered by the different data streams, but also by the fact that the fundamental biological processes in terrestrial and oceanic ecosystems are poorly understood and lack a mechanistic theoretical underpinning. The challenging way forward is module diversity and the inclusion of system components that can detect surprises.

Seasonal cycle and variability of the trend of column-averaged methane from GOSAT observations

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Methane concentration in the atmosphere varies in multiple time scales, and the variations are driven by the changes in the sources and sinks, i. e. in total budget, of methane. The long-term trend of global methane concentration has varied significantly over the past 15 years: in the early 2000s methane concentration increased slowly and the growth rate was nearly constant, while during the last years the concentration has rapidly increased. The reasons for these changes in the trend are not clear. Methane concentration varies also seasonally, the seasonal cycle is a complex result of the seasonal variability in natural and anthropogenic sources and sinks. Deeper knowledge of these variations in different time scales and regions is crucial for understanding the contribution of each source and sink, and also when trying to predict future methane concentrations and their impact on climate. To study these global variations of methane, we use column-averaged methane concentrations observed by the Greenhouse Gases Observing Satellite (GOSAT), which provides near global observations of column-averaged dry air mole fraction of methane (XCH_4).

In this study, we describe the seasonal cycle and variability of the trend of XCH_4 from 2009 to early 2016 based on GOSAT XCH_4 observations, by applying dynamic linear model (DLM) which models the cycle with harmonic components and is able to consider nonlinear trends. We used XCH_4 concentrations retrieved by National Institute for Environmental Studies (NIES) retrieval algorithm Version 02.21 (V02.21). The focus is on 12 Total Carbon Column Observing Network (TCCON) sites and 13 modified terrestrial TransCom regions over the globe. The latitudinal dependence of the cycle and variability of the trend are studied over Africa and Europe, excluding the highest latitudes. At TCCON sites we estimate the accuracy of GOSAT observations by comparing the seasonal cycle and variability of the trend based on GOSAT data to the cycle and trend based on TCCON data. The preliminary results show that there are clear regional features in the seasonal cycle and in the variability of the trend of XCH_4, indicating that the regional features may have a large contribution to the regional concentrations. For example, the peak-to-peak amplitude of the seasonal cycle is very sensitive to the regional sources and sinks. The cycle and variability of the trend of XCH_4 observed by GOSAT and TCCON are in generally good agreement. Based on the results, the seasonal cycle is stronger in the Northern Hemisphere, which is coherent with previous studies. The results indicate that the dynamic linear model approach is useful in quantifying the variability of the trend and seasonal cycle.

Global CFC-11, CFC-12, HCFC-22, CCl4, CH4, N2O measurements with MIPAS: validation, climatologies and trends

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MIPAS (Michelson Interferometer for Passive Atmospheric Sounding) on board the ESA ENVISAT spacecraft has been taking limb emission measurements of ozone profiles from 2002 to April 2012, with global coverage under day and night conditions. Level 2 Scientific Processor based at KIT IMK retrieves corresponding profiles based on constrained nonlinear least squares fitting of measured limb spectral radiance to modeled spectra.

We present recent validation of CFC-11, CFC-12, HCFC-22, CCl4, CH4, N2O vertical profiles retrieved from MIPAS spectra against ACE-FTS measurements. Climatologies derived from datasets will be discussed. Linear trends obtained with multi-linear regression model will be presented.

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High Resolution Global Terrestrial Carbon Flux: Evaluations and Applications

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Estimating global scale of the terrestrial carbon flux change with high accuracy and high resolution is important to understand global environmental changes. Furthermore the estimations of the global spatiotemporal distribution may contribute to the political and social activities such as REDD+. In order to reveal the current state of terrestrial carbon fluxes covering all over the world and a decadal scale. The satellite-based diagnostic biosphere model is suitable for achieving this purpose owing to observing on the present global land surface condition uniformly at some time interval. However the satellite-based diagnostic model can simulate the terrestrial carbon flux in only a few decadal periods due to the limitations of satellite data, so we cannot calculate back to 100 years ago. Therefore the model estimations have the potential to underestimate the annual terrestrial carbon fluxes as a result of doing spin-up to the steady state. Because the steady state is not the present day but pre-industrial era, so the carbon flux becomes to zero value throughout the world. In this study, we optimized the spin-up time of the terrestrial biosphere model (BEAMS), and estimated the global terrestrial carbon fluxes with 1km grids. Then we evaluated our new carbon flux estimations on various spatial scales and showed the transition of forest carbon stocks in some regions. The modification of spin-up time was made in each sub continental region using estimations of carbon fluxes by the atmospheric transport model (GOSAT L4A global CO2 flux). First, we made the BEAMS steady state by the spin-up run for 10000 years, and then the carbon amounts in the biomass and soil polls was adjusted to fit the GOSAT carbon flux. Our results indicated that the estimated accuracy improved significantly using the two satellite observation data (GOSAT as atmospheric information, and MODIS as land surface information). Annual global carbon fluxes were indicated similar values between BEAMS, GCP estimations and other model results, and perhaps these may be reasonable trends. We evaluated our new carbon flux estimations using the flux tower measurement (FLUXNET2015 Datasets) in a point scale. We used 166 sites data for evaluating our model results. These flux sites are classified following vegetation type (DBF, EBF, ENF, mixed forests, grass lands, croplands, shrub lands, Savannas, wetlands). In point scale, the BEAMS estimations was underestimated compared to the flux measurements in the case of carbon uptake and release. For understanding the transition of carbon stock, we compared our NEP with other results for REDD+ implementations. We could estimate the changes uniformly in the same way in any region.

A joint CO-CO_2 inversion system for studying the effect of drought on the carbon cycle

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Droughts impact the carbon cycle by enhancing biomass burning, and by reducing the carbon uptake by the biosphere. Droughts are expected to increase under future climate change. Therefore a good understanding of the feedback processes between droughts and the carbon cycle is important for accurately predicting future carbon dioxide (CO_2) levels in the atmosphere. An important tracer for biomass burning is carbon monoxide (CO). By combining the information from both CO and CO_2 ground-based and satellite data in an inverse modelling setup, it is possible to separately constrain the biomass burning and biosphere atmospheric fluxes of CO_2.

Within the TM5-4DVAR inverse modelling system, we implemented a joint CO-CO_2 inversion system. Biomass burning CO emissions to the atmosphere are constrained using CO observations. We use available CO:CO_2 emission ratios to calculate the direct biomass burning CO_2 flux based on derived CO emissions. The CO_2 exchange between the biosphere and atmosphere is then inferred using CO_2 measurements.

We present a series of Observation System Simulation Experiments (OSSEs) by which we test the performance of the coupled system. Synthetic data is produced using known fluxes, which we then attempt to retrieve starting from perturbed prior fluxes. The coupled system is able to improve the comparison between the modelled CO and CO_2 and the synthetic observations, similarly to the individual CO and CO_2 inversions. By including CO observations as an additional constraint for the biomass burning flux to the atmosphere, our inversion system provides a powerful tool for investigating the ecosystem sensitivity to droughts.

Assessing the inter-annual variability of wetland methane emissions

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Methane (CH_4) is an important anthropogenic greenhouse gas, contributing approximately 30% of the radiative forcing due to long-lived greenhouse gases since the industrial revolution, second only to carbon dioxide (CO_2). Global atmospheric concentrations of CH_4 are now approximately 1810 ppb, an increase of over 1000 ppb from pre-industrial level. However, it is the variability in the growth rate, particularly in recent years that is still widely not understood. Surface observations from a range of networks (NOAA, AGAGE, CSIRO and UCI) showed that the growth rate of atmospheric methane had been steadily declining over the last three decades. As atmospheric methane appeared to stabilise, suggesting an equilibrium between the various sources and sinks, the sudden and unexpected renewed growth from 2007 has highlighted significant gaps in our understanding.

The main sources of atmospheric methane are natural wetlands, rice cultivation, fossil fuel production, livestock and biomass burning. Of these, wetland emission contribute between 20-40% of the total global CH_4 emissions but there is a significant lack of understanding regarding their variability and importantly, their potential response to climate change.

The emission of methane from wetland regions, in particular the spatial and temporal variability, is crucially important to understanding the current and future Earth system and yet estimates of these emissions remain highly uncertain. This work uses both top-down and bottom-up estimates of wetland emissions and through comparison with measurements of atmospheric CH_4 made from the GOSAT satellite, assesses the temporal and spatial variability of these emission datasets and tests how well the observed methane wetland emissions are represented within land system models.

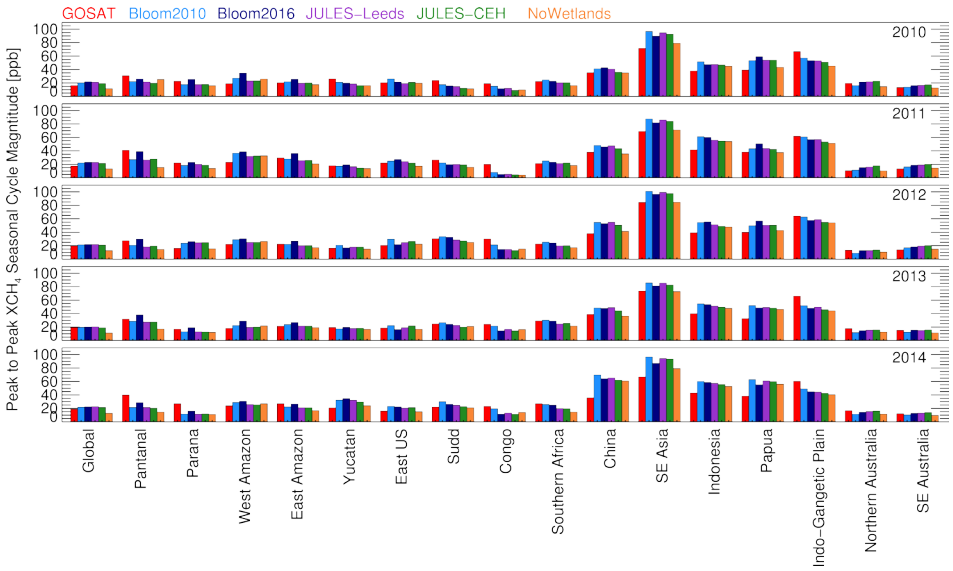

Figure 1: *Peak to peak seasonal cycle magnitude for the observation data and the model simulations using different wetland emissions.*

Relationship between biomass burning emissions and GOSAT XCO_2 and MOPITT CO changes over fire affected regions

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The carbon dioxide (CO_2) and carbon monoxide (CO) emissions released from biomass burning significantly affect the seasonal and interannual variations of atmospheric CO_2 and CO concentrations. Based on long-term (July 2009-June 2015) retrieved datasets by the Greenhouse gases Observing SATellite (GOSAT) and Measurement of Pollution in the Troposphere (MOPITT), we analyzed the seasonal cycle and interannual variations of column-averaged volume mixing ratios of atmospheric carbon dioxide (XCO_2) and CO in four fire affected continental regions. The results showed that Northern Africa (NA) experienced the largest seasonal variations after removing its regional trend of XCO_2 with peak-to-peak amplitude of 6.2 ppm within the year, larger than central South America (CSA) (2.4 ppm), Southern Africa (SA) (3.8 ppm), and Australia (1.7 ppm). Furthermore, we investigated the correlations of XCO_2 variations and fire CO_2 emissions. The detrended regional XCO_2 (ΔXCO_2) was found to be positively correlated with the fire CO_2 emissions during the fire activity period but with different seasonal variabilities. NA recorded the largest change of seasonal variations of ΔXCO_2 with a total of 12.8 ppm during fire seasons, higher than CSA, SA and Australia with 5.4, 6.7, and 2.2 ppm, respectively. During the fire episode, the positive ΔXCO_2 was noticed during June-November in CSA, December to next June in NA, and May-November in SA. The Pearson correlation coefficient between the variations of ΔXCO_2 and fire CO_2 emissions achieved the best correlations in SA ($R=0.77$ and $p<0.05$). The consistent temporal patterns of fire CO_2 emissions and CO noted good agreement in the four fire affected regions with the highest correlation in SA ($R=0.96$ and $p<0.05$). Meantime, CO and ΔXCO_2 achieved a strong temporal relationship ($R=0.88$ and $p<0.05$) (*Shi et al.*, 2017). Therefore, we can conclude that fire CO_2 emissions contributed to the temporal variations of GOSAT ΔXCO_2.

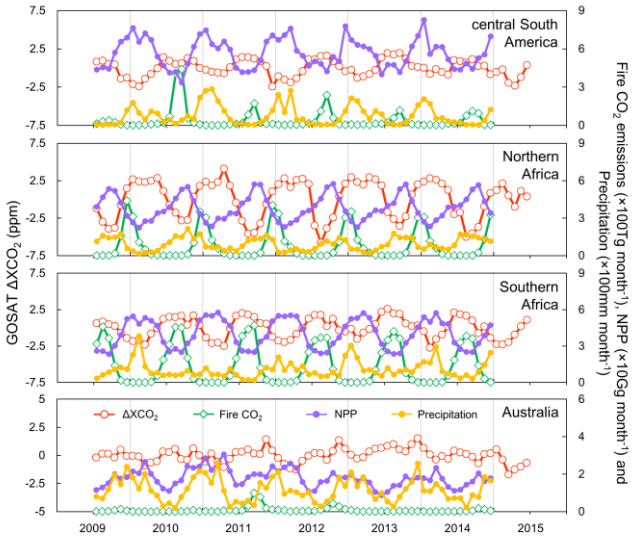

Figure 1: Monthly variations of GOSAT ΔXCO_2, fire CO_2 emissions, NPP and precipitation in the four fire affected regions during the period of July 2009 to June 2015.

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Carbon Balance under Changing Processes of Arctic and Subarctic Cryosphere (CARB-ARC project)

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The higher northern latitudes are especially sensitive to climate change, indicated by above-average rising temperatures. A considerable positive feedback on global warming is likely once additional carbon is liberated from thawing groun. The quantification and monitoring of physical processes of the circumpolar terrestrial cryosphere are highly important for the understanding of climate system feedbacks, especially concerning linkages between the atmosphere and soil/biosphere.

Space-borne derived global long-term datasets of high temporal resolution are the only means to obtain information on some of the relevant processes, especially given the hindered accessibility of these hostile environments. The project is concerned with using novel space-borne observations on land surface parameters and atmospheric greenhouse gases, *in situ* CO_2 and CH_4 flux measurements and Earth System Models, to synergistically retrieve information on the seasonal cycle of the high-latitude land surface carbon exchange processes. The scope of the Finnish Academy funded CARB-ARC project (Fig. 1) is to develop and demonstrate continental-scale mapping of CO_2 and CH_4 sources and sinks in the boreal forest, subarctic and arctic zones based on the developed techniques. In this presentation we will discuss the first results of the project.

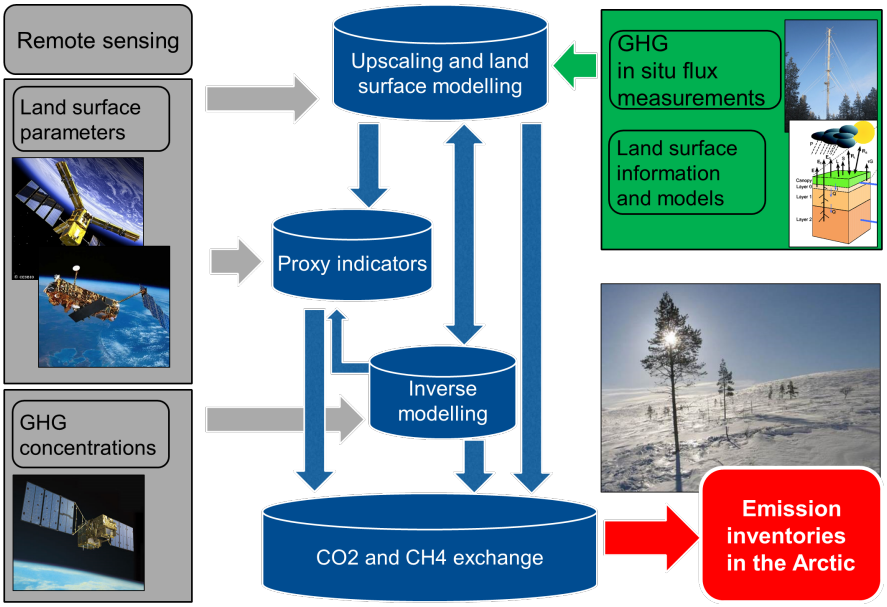

Figure 1: ***Research strategy of CARB-ARC project using top-down and bottom-up approaches***

GES DISC Greenhouse Gas Datasets and Associated Services

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NASA Goddard Earth Sciences Data and Information Services Center (GES DISC) archives and distributes rich collections of data on atmospheric greenhouse gases from multiple missions. Hosted data includes the Atmospheric Infrared Sounder (AIRS) mission which has observed CO2, CH4, ozone, and water vapor since 2002. GES DISC archives legacy data of water vapor and ozone retrievals from TIROS Observational Vertical Sounder (TOVS) and Upper Atmospheric Research Satellite (UARS) going back to the late 70's. GES DISC also archives and supports data for seven projects from the MEaSUREs (Making Earth Science Data Records for Use in Research Environments) program which includes ozone and water vapor. Data from the more recent A-Train satellite constellation is also available. A-Train data includes: (1) Aura-(OMI and MLS) ozone, nitrous oxide and water vapor since 2004, and (2) OCO2 CO2 data since 2014. Additional CO2 observations since 2009 from Atmospheric CO2 Observations from Space (ACOS) are also archived at GES DISC. The most recent dataset that GES DISC archives is methane flux for North America under NASA's Carbon Monitoring System (CMS) project. This data contains estimates of methane emission in North America based on an inversion of the GEOS-Chem chemical transport model constrained by GOSAT observations (Turner et al., 2015).

Along with the data stewardship, an important mission of GES DISC is to enhance the usability of data and broaden the user base. Users have unrestricted access to a new user-friendly search interface. Our new "Greenhouse Gas Datalist" allows users to access the greenhouse gas data variables in one place, with variable subsetting, format conversion, quality screening, and quick browse, are among the services available in the new user-friendly interface. The majority of the GES DISC data are also accessible through OPeNDAP (Open-source Project for a Network Data Access Protocol) and WMS (Web Map Service). These services add more options for specialized subsetting, format conversion, and image viewing. More data scouting, preview, and preliminary analysis are available in the web interface "Giovanni" that offers simple and intuitive ways to visualize, analyze, and access Earth science data without having to download the data. Giovanni provides a bridge between the data and science and has been very successful in opening the data for educational use and for users with limited resources.

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6 Solar Induced Fluorescence for Identifying Natural Sources and Sinks

On-going challenges and future perspective of SIF monitoring by GOSAT and GOSAT-2

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Atmospheric concentrations of greenhouse gasses, including CO_2 and CH_4, have increased due to human activities, such as fossil funeral burning and land use change, and this increase is the main driving cause of climate change in global scale. To deal with this issue, it is necessary to monitor the spatial distribution and temporal dynamics of GHGs concentrations and their emission and sequestration with underlying mechanisms. Terrestrial ecosystem, which is a large carbon sink, uptakes 31 % of anthropogenic CO_2 through photosynthesis by plants (Global Carbon Project 2016). Since photosynthetic process is quiet sensitive to meteorological conditions such as radiation, temperature and precipitation, the CO_2 absorption by terrestrial ecosystems shows large temporal variations and causes uncertainty of future prediction. So, a lot of efforts have been made to understand the spatial and temporal dynamics of photosynthetic CO_2 absorption of vegetation by in-situ observation, ecosystem model and satellite remote sensing.

In recent years, solar-induced chlorophyll fluorescence (SIF) monitoring by GHGs observation satellites, such as GOSAT and OCO-2 is drawn considerable attention as a new technique to evaluate CO_2 uptakes of terrestrial ecosystem. The chlorophyll fluorescence is weak radiation that emitted by chlorophyll in the photosynthetic process to release the extra energy, and in plant ecophysiology it has been a biophysical index to examine the photosynthetic responses to environmental stresses such as extreme temperatures and drought. Joiner et al. (2011) and Frankenberg et al. (2011) have suggested that TANSO-FTS, the sensor on GOSAT could detect overlapping part of emitted by terrestrial vegetation and Fraunhofer lines, which are dark lines of solar spectrum. Since SIF strongly related to photosynthetic process itself, it would provide us a lot of information about CO_2 function of terrestrial ecosystems. However, since those satellites are designed to monitor GHGs, there are several problems to use satellite measured SIF data to understand photosynthetic process; footprint size and frequency of the data.

In this talk, we will present our on-going and future challenges by GOSAT and GOSAT-2 to observe such photosynthetic activity of terrestrial ecosystems and its possible consequences with the atmospheric CO_2 concentration from national, continental to global scales under climate change.

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Using solar-induced chlorophyll fluorescence (SIF) to constrain global gross primary productivity in the process-based terrestrial biosphere model BETHY-SCOPE

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The Carbon Cycle Data Assimilation System enables the synthesis of model and observational information to constrain the evolution of a terrestrial biosphere model (*Kaminski et al.*, 2013). Previously, observational data such as atmospheric CO_2 and/or FAPAR have been used. We extend this system to ingest observations of solar-induced chlorophyll fluorescence (SIF) by incorporating the SCOPE model. This allows SIF observations to constrain uncertain model process parameters and the carbon flux gross primary production (GPP). We use satellite SIF observations from OCO-2 for 2015 to constrain global spatiotemporal patterns of GPP. Furthermore, we present two separate assimilation cases. The first case uses model predicted leaf area and the second prescribed leaf area. Development of this data assimilation system to estimating GPP will help disaggregate the net terrestrial carbon flux into its component fluxes.

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Radiance offset correction for observing solar-induced chlorophyll fluorescence from GOSAT

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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. Not all the absorbed solar energy by chlorophyll can be used for photosynthesis. SIF is a part of this unused energy emitted as radiation at longer wavelength (red and far-red domain) compared to the excitation wavelength. SIF includes information on partitioning of the absorbed solar energy and thus is considered to be a better proxy for the photosynthetic activity compared to the conventional vegetation indices. Several studies showed that SIF could be retrieved 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. Therefore, the zero-level offset correction becomes important to obtain the SIF accurately.

The zero-level offset can be evaluated from the retrieved filling-in signal (= zero-level offset + SIF) over the areas where the value of SIF is expected to be zero. We retrieved the filling-in signal using the same method as the previous studies from GOSAT short-wavelength infrared spectra processed by the version 161 Level 1 algorithm. Concerning Antarctica, the value of zero-level offset was small compared to the values shown in previous papers likely because of improvement in the Level 1 algorithm. However, zero-level offset's dependence on the observed radiance was the same. We investigated the zero-level offset for clouds and bare soils and confirmed its applicability to the offset correction. Temporal change of the zero-level offset was then clarified. Furthermore, validity of the derived SIF was investigated through comparison with SIF derived by numerical model.

OCO-2 advances photosynthesis observation from space via solar-induced chlorophyll fluorescence

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The quantification of CO_2 uptake through photosynthesis, denoted as gross primary production (GPP), remains a pivotal uncertainty in understanding global carbon cycle dynamics. The advent of space-borne solar-induced chlorophyll fluorescence (SIF) potentially represents a major breakthrough in terrestrial GPP monitoring. However, the extent to which SIF tracks spatiotemporal variations in GPP remains unresolved. OCO-2's unprecedented data acquisition rate and fine spatial resolution permit the first direct validation against ground/airborne observations and relating to GPP at various scales. We show strong correspondence between SIF and GPP globally in both time and space using empirical orthogonal function (EOF), and consistent linear SIF-GPP relationships at eddy-flux sites across diverse biomes, supporting the central importance of high-quality satellite SIF datasets for studying terrestrial ecosystem and carbon cycle dynamics.

Assessing seasonal cycle of photosynthesis by solar induced fluorescence in Fenno-Scandinavia

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Recent observations of chlorophyll fluorescence (ChlF) from space provide a useful proxy for photosynthesis. These observations can be used to increase our understanding of the terrestrial carbon cycle and to improve current land surface models (LSMs), enhancing their predictive power in the context of climate change. We have implemented a model of ChlF to a JSBACH LSM (*Thum et al.*, 2017), which is part of Max Planck Institute's Earth System Model. The ChlF model is process-based, but lacks currently a detailed parameterization for the seasonally changing ChlF related variables, such as the amount of active reaction centers. However, this implementation coupled the ChlF model with the Farquhar's biochemical model so that the seasonal cycle took place also for ChlF.

We made comparisons with the forest CO_2 flux measurements, from which the seasonal cycle of gross photosynthesis (GPP) can be deduced, and satellite observations of solar-induced fluorescence (SIF) from GOME-2 and JSBACH model results. The observed SIF was able to track the seasonal cycle of photosynthesis and the model results predicted both GPP and SIF at the sites quite well. Also comparisons with observed fAPAR (fraction of photosynthetically active radiation) data were done. JSBACH was not as successful in simulating fAPAR and it was not as good proxy for GPP as SIF. The slope between fAPAR and GPP differed between two northern and two southern sites, both in simulations and observations.

In addition to the site level simulations, a regional simulation was done for the Fenno-Scandinavian region. The seasonal cycle in the northernmost region (north of 66°N) of the remotely sensed SIF showed maximum value in August, whereas modelled SIF and GPP as well as up-scaled observation-based GPP product had largest value in July. This might reflect the difficulties in observing the high latitudes by satellite. In the southernmost region (south of 58°N) both observed SIF and observation based GPP product estimated highest uptake in June, whereas the model estimates predicted the maximum to occur one month later. This discrepancy was likely due to the missing crop dynamics not currently implemented in the model.

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Seasonal dynamics and inter-annual variation of solar-induced chlorophyll fluorescence and gross primary production in North, Central, and South America during 2000-2016

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The relationships between chlorophyll content, light absorption by chlorophyll, solar-induced chlorophyll fluorescence (SIF) and gross primary production (GPP) of terresrial vegetation are complex and dynamic under varying plant function types, atmospheric CO_2 concentration, weather and climate. Here we first present a data analysis and modeling study that combines GOME-2 SIF data (2007-2016) and GPP data (2007-2016) from the Vegetation Photosynthesis Model (VPM) (Xiao et al., 2004; Zhang et al., 2016). VPM uses the concept of chlorophyll content and the fraction of photosynthetically active radiation (PAR) absorbed by chlorophyll ($FPAR_{chl}$), MODIS-based vegetation indices (EVI-relevant to vegetation chlorophyll content; LSWI- relevant to land surface water content), and climate data (air temperature and PAR) to estimate daily GPP. We report the sensitivity of GPP from various biomes in North America (Canada, USA and Mexico) to climate variability, including the severe drought in 2012. We also report GPP dynamics from Central and South America. Secondly, we introduce an *in-situ* observation study that integrates SIF measurements with CO_2 eddy flux measurements in a tallgrass prairie site in Oklahoma. Thirdly, we introduce the NASA Geostationary Carbon Cycle Observatory (GeoCARB) mission, which was selected in December 2016 by NASA. The GeoCarb mision is planning to be launched by late 2021 or early 2022. The GeoCarb mission will provide daily SIF data for North, Central and South America, in addition to atmospheric CO_2, CO and CH_4 concentration data. The unprecedented daily SIF data can be used to better understand the relationship between chlorophyll content, light absorption by chlorophyll, SIF and GPP at diurnal, daily and seasonal scales. When an integrated in-situ, airborne and spaceborne SIF observation framework is combined with other observation systems (e.g., Ameriflux), we can develop a new and improved capacity to (1) monitor, report and verify the terrestrial biospheric carbon fluxes in North, Central and South America, and (2) carry out a variety of applications for agriculture, food security and forestry.

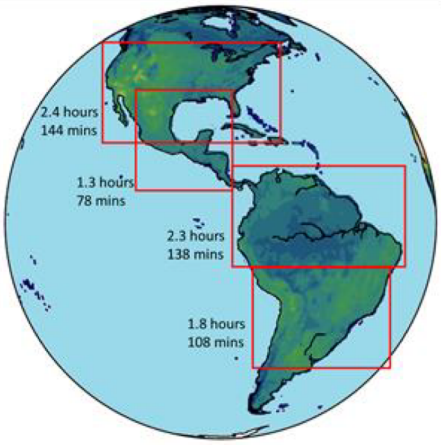

Figure 1. Possible scan blocks by GeoCarb mission for a 85°W geostationary orbital slot.

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7 Future Missions and Observing Strategies

Advances in Pulsed Lidar Measurements of XCO_2 from Aircraft and in Scaling for Space

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March 22, 2017

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We have demonstrated an improved pulsed, multiple-wavelength integrated path differential absorption lidar for measuring the atmospheric CO_2 concentrations. The CO_2 Sounder lidar measures the shape of the 1572.33 nm CO_2 absorption line and the range to scattering surfaces, including the ground and the tops of clouds. Airborne measurements have used both 30 and 15 fixed wavelength samples distributed across the line. In recent ASCENDS airborne campaigns the lidar used a new high precision step-locked laser seed source, and sensitive HgCdTe APD detector in the receiver. Analyses of 2014 airborne measurements show the retrievals of lidar range and XCO_2 worked well when measuring over variable topography and through thin clouds and aerosols. In several flights the agreement of the lidar retrievals with the in-situ measured XCO_2 was better than 1ppm. Two additional ASCENDS flights were made in February 2016 and included measurements made over a desert and extended ones over snowfields. The 2016 lidar configuration used a larger laser spot size to reduce speckle noise and a receiver with improved optical transmission. These changes improved the lidar sensitivity x3. The 2016 retrievals show 0.7 ppm precision over the desert in 1-second averaging time, and agreed with the in-situ measured column XCO_2 to within 0.5 ppm.

We have also updated our measurement model and retrieval approach for the airborne lidar. The CO_2 absorption line shape is fit to the received energy at each wavelength to determine XCO_2. The receiver model includes effects of solar background, photon detection shot noise, detector dark current, preamplifier noise and laser speckle. The retrieval employs a least-square fit to the CO_2 line that is linear in optical depth (the logarithm of the optical transmission measurements). The XCO_2 is proportional to the scaling factor of optical depth determined from the line fit. There are also terms to solve for and mitigate potential sources of measurement bias, including Doppler shift and dependence of receiver transmission versus wavelength. The receiver model further gives insight about the effects of various instrument parameters and the difference between the atmosphere model used in the curve fit and the actual atmosphere. For example, we can use the model to estimate the biases in the retrieved XCO_2 from small errors in the meteorological data used to generate the line shape for retrieval. The random errors from the 2016 airborne measurements agree well (within a factor of 1.4) with the measurement model.

Our team has also demonstrated other key capabilities needed for a space version of the lidar. One is a new fiber laser power amplifier that allows increasing the airborne laser transmitter to 20W average power. Ongoing laser development is improving the engineering and the ruggedness of the key laser components. The work is scheduled to take a laser and a detector module through space environmental testing to achieve TRL 6 by December 2017. When the lidar performance model is evaluated for a space design that uses 20W laser power, a 1.5 m diameter telescope, and is at 400 km orbit altitude, the results show random errors of 0.4 ppm over desert surfaces in 1 second averaging time. This is 3 times better than the present ASCENDS mission requirement.

OXYCO2: A New Experiment for the Measurement of the CO_2 Distribution in Stratosphere and in the Upper Troposphere

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We present the results of a study for a new strategy for the measurement of the CO_2 distribution in the stratosphere. The proposed experiment (Carlotti et al. 2016) is based on an orbiting limb sounder that measures the atmospheric emission in the spectral regions of both the Thermal InfraRed (TIR) from 685 to 930 cm^{-1} and Far-InfraRed (FIR) from 80 to 180 cm^{-1}. The idea is to exploit the contribution of the pure rotational transitions of molecular oxygen in the FIR to determine the atmospheric fields of temperature and pressure that are necessary to retrieve independently the distribution of CO_2 from its rovibrational transitions in the TIR. The instrument considered to test the new strategy is a Fourier transform spectrometer with two output ports hosting a FIR detector devoted to measure the O_2 transitions, and a TIR detector devoted to measure the CO_2 transitions. Instrumental and observational parameters of the proposed experiment have been defined by exploiting the heritage of previous studies and operational limb sounders. The performance of the experiment has been assessed with two-dimensional retrievals on simulated observations along a full orbit. For the purpose, optimal spectral intervals have been defined using a validated selection algorithm. Both precision and spatial resolution of the obtained CO_2 distribution have been taken into account in the assessment of the performance of the proposed experiment. We have seen that the O_2 spectral features significantly contribute to the performance of the CO_2 retrieval, and that the proposed experiment can determine the two-dimensional distribution of the CO_2 volume mixing ratio with a precision of the order of 1 ppmv in the 10-50 km altitude range. The error budget, estimated for the test-case of an ideal instrument and neglecting the spectroscopy errors, indicates that, in the 10-50 km altitude range, the total error of the CO_2 fields is dominated by the random component. This could also be the case at higher altitudes, provided the retrieval system is able to model the non-local-thermal-equilibrium conditions of the atmosphere. The best performance is obtained at altitudes between 20 and 50 km where the vertical resolution ranges from 3 km to 5 km and the horizontal resolution is of the order of 300-350 km depending on latitude.
The same experiment could be used to observe the distribution of several greenhouse gases spectroscopically active in the observed spectral region.

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The OCO-3 Mission : Updated Overview of Science Objectives and Status

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The Orbiting Carbon Observatory 3 (OCO-3) will continue global CO_2 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) (launch readiness in early 2018.) This talk will focus on the science objectives as well as updated simulations to predict quality of OCO-3 science data products.

The low-inclination ISS orbit lets OCO-3 sample the tropics and sub-tropics across the full range of daylight hours with dense observations at northern and southern mid-latitudes (+/- 52º). The combination of these dense CO_2 and SIF measurements provides continuity of data for global flux estimates as well as a unique opportunity to address key deficiencies in our understanding of the global carbon cycle. The instrument utilizes an agile, 2-axis pointing mechanism (PMA), providing the capability to look towards the bright reflection from the ocean and validation targets.

The PMA also allows for a snapshot mapping mode to collect dense datasets over 100km by 100km areas. Measurements over urban centers could aid in making estimates of fossil fuel CO_2 emissions. This is critical because the largest urban areas (25 megacities) account for 75% of the global total fossil fuel CO_2 emissions, and rapid growth (> 10% per year) is expected in developing regions over the coming 10 years.

Similarly, the snapshot mapping mode can be used to sample regions of interest for the terrestrial carbon cycle. For example, snapshot maps of 100km by 100km could be gathered in the Amazon or key agricultural regions. In addition, there is potential to utilize data from ISS instruments ECOSTRESS (ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station) and GEDI (Global Ecosystem Dynamics Investigation), which measure other key variables of the control of carbon uptake by plants, to complement OCO-3 data in science analysis.

Optimising Imaging Fourier Transform Spectrometer for GHG from LEO

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Fourier Transform Spectrometers (FTSs) have been used in numerous atmospheric sensing missions over the past decades. Spectroscopists aiming at automated and dependable retrieval especially appreciate their instrument line shape stability easily modeled by an analytic function across the entire spectral range. This feature is in part what led to FTS being favored in hyperspectral IR sounders for LEO and GEO weather satellites in both the US and Europe. Yet apart from the upcoming MTG-IRS none of these sensors properly exploit the natural fit of the FTS for imaging configurations. In this paper we show how imaging FTS can be optimized for retrieving Green House Gas (GHG) total column concentration in Low Earth Orbit (LEO).

While 1-D imaging dispersive spectroscopy presents a natural fit for the scene scanning inherent to LEO, the imaging FTS can match the across track definition while accepting a much larger throughput in the along-track direction. This important scene photon collection advantage can be put to good uses to overcome the so called "multiplex disadvantage" or distributed photon noise common to FTS. By carefully tailoring the IR bands to the minimum required for accurate gas species retreival, two critical benefits are obtained:

1. The distributed photon noise is reduced
2. The limitation of the free spectral range allows for optimisation of the interferogram sampling and important reduction in detector frame rate.

This approach yields detector requirements within today's COTS IR array detectors availability and allows reaching higher performance in the spatial/temporal/SNR trade space as seen below.

Sensor input aperture	8 cm
Detector size	128 x 128 (per band)
Pixel scale	500 km x 500 km
Field of Regard (FOR)	64 km x 64 km
Swath coverage per orbit	128 km (interleave mosaic)
Dwell Time per FOR	4 sec
Pointing mirror scan during dwell	+/- 1.2°
Pointing stability (1/10 pixel criteria)	75 μrad RMS
Spectral bands: ➢ O2: B-1 ➢ CO2: B-3, B-4 ➢ CH4: B-2, B-5 ➢ CO: B-5	 Band 1: 7880-8000 cm^{-1} Band 2: 6190-6250 cm^{-1} Band 3: 5980-6030 cm^{-1} Band 4: 4980-5010 cm^{-1} Band 5: 4190-4260 cm^{-1}
Spectral grid	0.2 cm^{-1} (MOPD = 2.5cm)
SNR per pixel	> 180

Figure 1: *Sample specification of GHG tailored LEO IFTS*

The above instrument design allows to generate 3490 independent ground measurements per second with an SNR high enough to yield valuable GHG retrievals. Previous missions like GOSAT-1 have helped to develop the retrievals and validate accuracy of FTS sensors. Adding strong imaging capacity will bring spatial and spectral resolution for GHG retrieval to another level.

Level 2 processing of MERLIN mission data

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The Methane Remote sensing Lidar mission, MERLIN, is dedicated to measurements of methane dry-air mixing ratio columns, XCH_4, with an IPDA (Integrated Path Differential Absorption) Lidar (*Kiemle et al*, 2011, *Pierangelo et al.* 2016). The Payload, as well as the level 1 processing development, is under the German Space Administration DLR responsibility, while the development of the level 2 processing and the host structure (PLDP for Payload data Processing) is managed by the French Space AgencyCNES.
We describe here the algorithms of the level 2 processing, that estimate XCH_4, as well as its associated error and weighting function, from the Lidar measured Differential Absorption Optical Depth provided in the level 1 product. These algorithms include, amongst other steps: an interpolation of meteorological data and a correction for the atmospheric pressure at target position, using the Lidar Range measurement; a correction for Doppler effect on emitted frequency; a computation of the weighting function based on methane absorption cross-sections from the 4A code (*Scott and Chédin,* 1981); an averaging of single shot pairs data along track and the associated bias correction.
Because for flux estimations, the requirements for random and systematic errors on level 2 products are stringent, great care is taken not to introduce additional errors from the ground processings. Some results of algorithm validation studies will be shown.

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Updated Global Error Characterization for a CO_2 Lidar Space Mission

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ASCENDS Ad Hoc Science Definition Team

A great deal of progress has been made in development of space-based, lidar sensing methods since the US National Academy of Sciences (NAS) 2007 Decadal Survey recommended the ASCENDS mission (Active Sensing of Carbon Emissions, Nights, Days, and Seasons) for NASA's next generation CO_2 observing system. Measurement of atmospheric greenhouse gases, principally CO_2 and CH_4, from space using active sensing techniques has significant advantages in comparison to passive remote sensing (e.g., Fig. 1), and such missions remain in consideration by the current NAS Decadal Survey for Earth Science 2017. In this presentation, we update the measurement error characteristics expected for an active CO_2 mission, test how these measurements will enhance our ability to quantify surface fluxes, and examine the potential role of active sensing to address carbon cycle issues as required for robust prediction of carbon-climate interactions.

Over the past decade, CO_2 lidar instrument concepts, retrieval approaches, and measurement techniques have matured significantly, driven by technology advances and by analysis of data from airborne simulators. Performance simulations updated to match the latest developments show substantially lower random errors, better spatial resolution, and more information content for global XCO_2 data (e.g., < 1 ppm error @ 1 Hz) than just a few years ago (*Kawa et al.*, 2010). Observing system simulation experiments using global flux inversion models show corresponding improvements in resolving surface fluxes and reducing flux uncertainties with these lidar data. Recent studies demonstrate the impact of errors in knowledge of the atmospheric state and bear on the consideration of coincident measurements of O_2 column in order to calculate dry air mole fraction. Investigation of prospective systematic (bias) errors, which are expected to be smaller for the lidar compared to passive measurements, provides guidance for setting instrument design requirements. We also assess the implications for targeting science objectives in key regions, and compare to actual observations from GOSAT and OCO-2.

The recent findings further affirm the expected benefits of ASCENDS for carbon cycle science. Active systems will provide GHG measurements of high quality, and full global and seasonal sampling that will contribute substantially to advancing knowledge of carbon flux distributions and their dependence on underlying physical processes in critical regions.

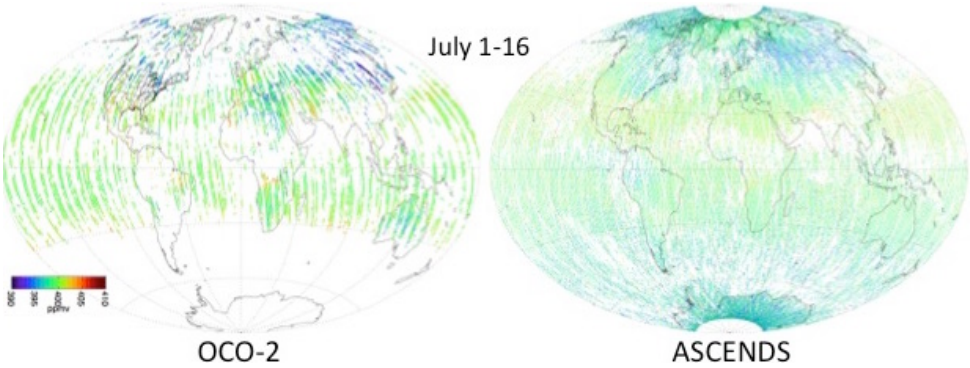

Figure 1. *Comparison of global sampling from OCO-2 for July 1-16, 2015 with that expected for ASCENDS.*

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The spectral sizing of ESA's future CO2 observing space mission

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To support the defintion of ESA's future carbon dioxide instrument, a dedicated study is performed evaluating different spectral setups of a three-band instrument concept covering the NIR ($\approx$ 760 nm), the SWIR-1 ($\approx$ 1.6 μm) and the SWIR-2 ($\approx$ 2.0 μm) spectral range. The feasibility studies for ESA's eighth Earth Explorer candidate mission CarbonSat resulted in an instrument concept with relatively low spectral resolution and high SNR, as compared to other current (GOSAT, OCO-2, TANSAT) and planned missions (MiroCarb). To evaluate the different spectral sizing concepts, we investigated in this study aerosol and cirrus induced errors as well as instrument related errors on XCO_2 due to ISRF distortion, stray light, detector non-linearity and instrument polarisation sensitivity. We considered four different instrument concepts from low to high spectral resolution, from low to high signal-to-noise, from narrow to wide spectral windows. Fig. 1. shows simulated sample spectra for each of these four instrument concepts. The induced errors are quantified for a global and an orbit ensemble of simulated measurements, where we utilised the RemoTeC retrieval algorithm, which has GOSAT and OCO-2 heritage and will be used for operational methane data processing for the future Sentinel-5 and Sentinel-5 Precursor mission. The analysis is a result of the ESA's funded *"Study on spectral sizing for CO_2 observations"*.

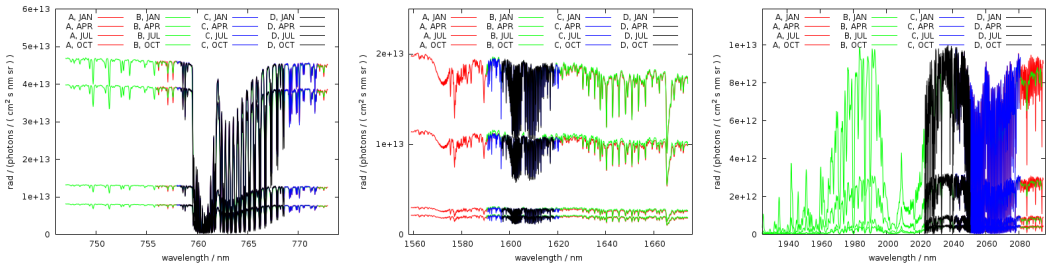

Figure 1: *Simulated spectra of NIR (left), SWIR-1 (middle) and SWIR-2 (right) band radiances for the four candidate instrument concepts.*

State of play for a European operational monitoring system for fossil CO_2 emissions

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Contributions from many experts
Major international institutions

As part of the European 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 further develop the first generation Copernicus Space Component to include measurements for fossil CO_2 emission monitoring. The greatest contribution to the increase in atmospheric CO_2 comes from emissions from the combustion of fossil fuels and cement production. Current uncertainties associated with their emission estimates at national and regional scales may translate into ill-informed policy decisions and limitations in assessing the effectiveness of CO_2 emission strategies.

In 2015, upon request of the European Commission, a group of experts outlined a holistic vision and a preliminary roadmap for a European integrated observation and inversion modelling system dedicated to the monitoring of fossil CO_2 emissions. The development and operation is proposed to be undertaken within the frame of the Copernicus Programme. The atmospheric measurements made by a combination of satellites and in-situ networks would be used in an operational system based on three complementary components consisting of measurements, bottom-up inventories and data-assimilation system.

Satellite and in-situ atmospheric measurements, in addition to bottom-up inventories, would enable the transparent and consistent quantitative assessment of CO_2 emissions and their trends at the scale of megacities, regions, countries, and the globe as well. Such a capacity would provide the European Union with a unique and independent source of information, which can be used to inform on the effect of policy measures, and to track their impact en-route towards decarbonizing Europe and meeting national emission reduction targets. Further, there would be potential synergies at international level with observation systems under discussion with other third parties.

This presentation provides an overview of the essential scientific and technical capabilities that are required to enable such an observation system. It also provides a status update of activities and dedicated studies currently undertaken to prepare for the implementation of the space component of this monitoring system.

The GeoCarb Mission

Berrien Moore III and Sean Crowell
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This paper presents a discussion of the GeoCarb Mission, which was recently selected as NASA's Earth Venture Mission-2. GeoCarb will fly an instrument that will provide measurements of atmospheric carbon dioxide (CO_2), methane (CH_4), and carbon monoxide (CO) from geostationary orbit at roughly 85°W. The GeoCarb mission will deliver daily maps of column integrated mixing ratios of CO_2, CH_4, and CO over the observed landmasses at a spatial resolution of roughly 5 x 8 km.

The instrument exploits four spectral regions: The oxygen A-band for pressure and aerosols, the weak and strong bands of CO_2 near 1.61 and 2.06 microns, and a region near 2.32 microns for CO and CH_4. The O_2 and CO_2 components are very similar to the instrument aboard OCO-2, and so we envision OCO-2 in geostationary orbit with the addition of a fourth channel to measure CO and CH_4, but without an oceanic capability. The chosen spectral channel for pressure and aerosols (0.765μm) permits measurement of Solar-Induced Fluorescence (SIF), which provides direct information about photosynthesis.

The 85°W slot allows observations of major urban and industrial regions in the Americas, large agricultural areas, and the expansive South American tropical forests and wetlands, which will help resolve flux variability for CO_2 and CH_4. As noted, the GeoCarb mission will produce daily maps at a spatial resolution of 5-8 km of the carbon gas concentrations and SIF. We believe that these persistent observations will provide the basis for a transformational improvement in our understanding of the carbon cycle, including climate-critical insights into the carbon-climate connection.

Recent studies on high latitude greenhouse gas observations from a highly elliptical orbit (HEO) mission

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Continuous space-based observations of atmospheric CO_2 and CH_4 are desirable for studies of the carbon cycle. Although geostationary (GEO) missions can provide observations of CO_2 and CH_4 multiple times per day during daylight for a given location, the high viewing angles from GEO poleward of ~55°N prohibit coverage of the Arctic and much of the boreal region. Two satellites with shortwave infrared (SWIR) imaging capability in a highly elliptical orbit (HEO) configuration offer the potential for quasi-geostationary coverage of CO_2 and CH_4 at northern high latitudes (~50-90°N). The Canadian Space Agency funded earlier Phase 0 and A studies for the "Weather, Climate and Air Quality" instrument suite, which included CO_2 and CH_4 observing capability, as an enhancement to a proposed operational meteorological mission. Simulations demonstrated that HEO CO_2 observations would be most effective at reducing flux uncertainties during the summer, when permafrost thaw is expected. Here we describe results of new studies on the feasibility of a standalone HEO air quality and greenhouse gas (GHG) mission including trade studies for an improved GHG instrument. We also present new HEO pointing strategies for cloud avoidance and briefly describe recent work on CO_2 retrievals in high latitude regions.

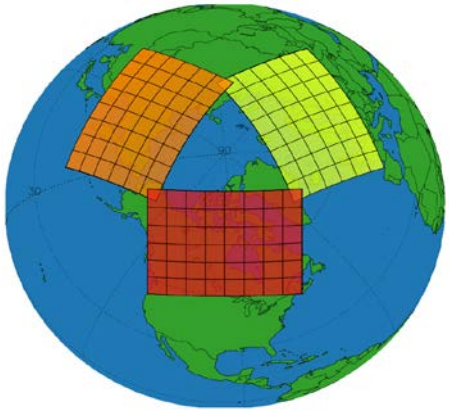

Figure 1: *Potential fields of regard for CO_2 and CH_4 observations from an imaging Fourier transform spectrometer (IFTS) in a highly elliptical orbit (HEO).*

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

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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. Though the current generation of carbon observing satellites has provided valuable data in regions that are not covered by surface *in situ* measurements, limited sampling of key regions and small but spatially coherent biases have limited the ability to estimate fluxes at the time and space scales needed for improved process-level understanding and informed decision-making. Next generation satellites will improve coverage in data sparse regions, either through use of active remote sensing, a geostationary vantage point, or increased swath width, but all techniques have significant limitations. The relative strengths and weaknesses of these approaches and their synergism have not been thoroughly and quantitatively examined. 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 observing system simulation experiments (OSSEs), with close collaboration in framing the experiments and in analyzing the results. Here, we report on the initial phase of this initiative, which focuses on creating realistic and physically consistent synthetic CO_2 and CH_4 observational datasets for use in inversion and signal detection experiments. These datasets have been created using NASA's Goddard Earth Observing System Model (GEOS) to represent the current state of atmospheric carbon species as well as best available estimates of expected flux changes. These include the growing uncertainty in urban fossil fuel emissions, the response of permafrost carbon to a warming climate, the balance of carbon uptake between tropical and mid-latitude forests, changes in the Southern ocean sink, and changes in both anthropogenic and natural methane emissions. This GEOS 'nature run' was then sampled by instrument simulators representing the most prominent observing strategies with a focus on consistently representing the impacts of random and systematic errors. These datasets will be made publicly available to support the international carbon modeling community and future mission planning activities. We will also discuss the need for further coordinated OSSE activities, including improved understanding of the diurnal cycle of cloud cover and inverse modeling assessments of carbon observing systems.

Status of MERLIN mission

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CNES, the French space agency, and the German DLR Space Administration, in order to strengthen their cooperation in space activities, develop an Earth-Observation satellite mission, dedicated to methane (CH_4) monitoring. After carbon dioxide, methane is the second most important anthropogenic greenhouse gas which contributes signicantly to human-induced global warming. The main science objective is to bring a significant improvement on the retrieval of CH_4 fluxes which requires 1% accuracy on CH_4 column averaged dry-mixing ratio, at a 50 km horizontal resolution. The MERLIN (MEthane Remote sensing LIdar missioN) mission is based on a small satellite for space-based measurement of spatial and temporal gradients of atmospheric methane columns on a global scale. The measurements of methane dry-air mixing ratio columns, XCH_4, are performed with an IPDA (Integrated Path Differential Absorption) Lidar (*Kiemle et al*, 2011,). The platform, a new MYRIADE-Evolution type, is developed under CNES responsibility, the payload is developed under DLR responsibility, while the processing and ground segments are shared between agencies. The current status of MERLIN project will be presented, including a description of the system, the satellite and the payload. Some results of the studies conducted to estimate the impact of MERLIN on methane flux retrievals will be shown, taking into account both random and systematic errors. Finally, we will also present some results of the DLR airborne lidar "CHARM-F" (*Amediek at al*., 2012), a keystone for the development and validation of MERLIN.

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The Role of CO observations in source attribution for the GEOCARB Mission

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The GEOCARB mission will measure simultaneously CO_2, CH_4 and CO from geostationary orbit at high spatial and temporal resolution. This offers the chance of reliable attribution of CO_2 sources to combustion and noncombustion processes. This requires some methodology in an inverse framework to separate these signals. Traditionally this is done using tracer-tracer correlations, i.e separation at the concentration level. In earlier papers we explored separation at the source level. We suggested that, even with reasonable uncertainty on emission factors, the separation at source level allowed reasonable attribution. In this talk we explore this problem further in the light of recent improvements in simulated retrievals of CO. We examine the robustness of this attribution to prior estimates of emission factors, the presence of mixed sources and uncertainties in transport. While the method can deal quite well with the first of these two uncertainties, spatial attribution, as well as quantification of overall sources, is highly sensitive to transport errors.

GOSAT observations and global carbon cycle

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Greenhouse gases Observing SATellite (GOSAT) has been monitoring atmospheric column carbon dioxide (XCO_2) and methane (XCH_4) concentrations from space since its launch in January 2009. The primary goal of GOSAT project is to successfully estimate global carbon budget on subcontinental scales using spatiotemporal distribution of XCO_2 and XCH_4. GOSAT observations have provided the basis for assessments of the values of space-based measurements of CO_2 and CH_4 concentrations. This work summarizes the benefit of GOSAT observations in the study of global carbon cycle based on previous studies using GOSAT observations, together with limitations due to data coverage and density. Moreover, we will introduce preliminary hearing results of scientific requirements to near future missions of greenhouse gases satellites observations.

Elements of a future Sentinel mission for imaging fossil fuel CO_2 emissions

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In the frame of the Copernicus programme, the European Commission (EC) and the European Space Agency (ESA) are jointly developing plans for complementing the current fleet of operational Sentinel missions. Among the identified priorities is a multi-component observing system, which is capable of quantifying fossil fuel CO_2 emissions (*EC, 2015*). The space component of such a system would require a constellation of satellites providing imaging capability with a spatial resolution on the order of 4 km^2 and a swath width around 200 km. These characteristics, as well as preliminary radiometric and spectral requirements, are similar to those of the CarbonSat mission, which has been extensively studied as candidate Earth-Explorer mission in ESA's Living Planet programme (*ESA, 2015*). Therefore the results of the industrial phase A/B1 studies performed for CarbonSat are considered as a starting point for defining a future Sentinel mission. In this presentation we present elements of the CarbonSat design studies, that are considered relevant for space-borne imaging of anthropogenic CO_2 emissions. Results from industrial pre-developments of key components, such as slit homogenisers, diffraction gratings and Sun diffusers, will be presented and their performance reviewed. In view of preliminary future mission requirements, instrument sizing principles are recalled, focusing on the trade-offs between spatial resolution, signal-to-noise ratio, swath width and spatial co-registration.

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Advanced tropospheric ozone monitoring by data fusion and assimilation

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Ozone is a significant greenhouse gas that is formed and destroyed by chemical reactions involving other species in the atmosphere and a key constituent for understanding the interactions between climate and chemistry. In contrast to most GHGs, tropospheric ozone is produced photo-chemically via its precursors, notably nitrogen oxides, carbon monoxide, CH4 and non-methane hydrocarbons, all of which have large anthropogenic sources. Crucial uncertainties however remain in the assessment of the tropospheric ozone budget, its precursors, and the chemical and physical processes involved. Large spatial and temporal variability is observed in tropospheric ozone, resulting from important regional differences in the factors controlling its concentration. For all these reasons, accurate global measurements of ozone vertical profiles are essential. Instruments developed over recent decades to monitor ozone from space exploit a large range of observation geometries and spectral regions. However, due to the inherent limitations of each space-borne measurement technique, none of the existing systems can cover the needs for accurate ozone observations from the surface up to the mesosphere. AURORA (Advanced Ultraviolet Radiation and Ozone Retrieval for Applications) is a three-year project supported by the European Union in the frame of its H2020 Call EO-2-2015 with the overarching objective to simulate the provision of synergistic data products, having unprecedented accuracy, for the vertical profiling of atmospheric ozone and to assess their quality with respect to the one expected for the operational products of the geostationary (GEO) mission Sentinel-4 and of the Low Earth Orbit (LEO) missions Sentinel-5p and Sentinel-5. The main scientific purpose of AURORA is to investigate the potential of synergistic exploitation of complementary measurements of ozone acquired in different spectral regions – from the UV over the visible to the thermal infrared - through the assimilation of fused GEO and LEO ozone profile products resulting from application of an innovative data fusion method. The impact of combining complementary capabilities of the atmospheric Sentinels observations, especially in terms of vertical sensitivity, might result in advanced performances that are of specific relevance for tropospheric ozone monitoring. An extensive ozone product validation system is being developed in the frame of the project to assure that the AURORA ozone profile and tropospheric ozone data products will be warily verified and documented by means of thorough QA/validation studies. In a longer term perspective, demonstration of successful application of the AURORA concept to ozone might foster further scientific and technological developments towards exploitation of this innovative approach for other GHGs monitoring.

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