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IG^{3}IS/TRANSCOM workshop

Inverse modelling of greenhouse gas fluxes from atmosphere observations

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Abstracts

Contents

Session 1: Combining multiple constrains

1a Global methane inversion in a multi-tracer framework

Yi Yin, Frederic Chevallier, John Worden, Christian Frankenberg

Variations in the recent global atmospheric methane (CH4) growth rate have been much debated with competing hypotheses including changes in different emission sectors, the hydroxyl (OH) sink, or the dynamics of the atmospheric transport. Here, we build a multi-tracer inversion framework that assimilates simultaneously the major tracers in the CH4 oxidation chain (CH4-CH2O-CO) that share OH as the common sink and optimizes the emission of each tracer and a scaling factor for OH per horizontal model grid at the same time. The total column retrievals of CH4 from GOSAT, CH2O from OMI, and CO from MOPITT are assimilated for the period from late 2009 to the end of 2017. We also include sensitivity analysis of GOSAT-CH4-only and surface-observation-only inversions to evaluate the impact of introducing additional tracers on the CH4 emission estimates and the differences in the information content between satellite and surface observations. This study analyzes regional CH4 emission changes and OH variations and their contributions to the global CH4 growth rates in recent years. Uncertainties due to different error assumption about the OH and the assimilating of chemically related tracers are also discussed.

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Session 1: Combining multiple constrains

1b High-resolution biospheric net and gross carbon fluxes derived from integrating eddy covariance measurements with remote sensing and machine learning

Martin Jung, Paul Bodesheim, Sophia Walther, Markus Reichstein

Partitioning anthropogenic emissions and natural biospheric CO2 exchange with inverse atmospheric modelling and data assimilation requires reliable constraints of both components with well characterized uncertainties. Spatially and temporally resolved products of biospheric CO2 fluxes are derived from integrating in-situ eddy covariance measurements with remote sensing and machine learning. Such data-driven products are advantageous over land surface model simulations due to the adaptiveness of machine learning methods and the strong observational constraints by satellite and station data. In addition, characterization of uncertainties in these data-driven products is, even though not trivial, less difficult compared to those of land surface model simulations. Here we aim at presenting a synthesis of previous activities to derive such data driven products of biospheric carbon fluxes, and to report on ongoing and future activities of advancing the products in terms of quality and resolution. The synthesis will focus on achievements with respect to accurately resolving the diurnal cycle with this approach as well as with respect to uncertainty characterization and quantification based on the FLUXCOM ensemble. We report about ongoing efforts to improve the approach further for example by incorporating very high frequency geostationary satellite data, more and better eddy covariance observations as well as methodological machine learning advances.

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Session 1: Combining multiple constrains

1c First results from a Carbon Cycle Fossil Fuel Data Assimilation System (CCFFDAS)

Thomas Kaminski (1), Marko Scholze (2), Peter Rayner (3), Michael Vossbeck(1), Michael Buchwitz (4), and Max Reuter (4): (1) The Inversion Lab (2) Lund University (3) Melbourne University (4) IUP, Bremen

We present first results from a Carbon Cycle Fossil Fuel Data Assimilation System (CCFFDAS) that is built around coupled process models of the terrestrial biosphere and of fossil fuel emissions. The CCFFDAS exploits several observational data streams, including atmospheric (X)CO2, nightlights, reported national totals for sectorial fossil emissions, and emission estimates for individual power plants. The data streams are linked to the process models by dedicated observation operators and are used to constrain a control vector of the models' process parameters. The calibrated model is then used to provide surface fluxes that are consistent with the observations and the model, together with estimated uncertainty ranges.

We employ the system to quantify the added value to be expected from the Copernicus High Priority Candidate Mission for Anthropogenic CO2 Monitoring relative to the global in situ CO2 sampling network. This added value is quantified in terms of uncertainty reduction of fossil fuel emissions on a global grid of 0.1 degree resolution. We explore the sensitivity of this added value with respect to influence factors such as the definition of the control vector or prior and data uncertainties.

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Session 1: Combining multiple constrains

1d Atmospheric COS and CO2 measurements to evaluate and optimize the gross primary productivity of land surface models

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Predicting the fate of the ecosystem carbon stocks and their sensitivity to climate change strongly relies on our ability to accurately model the gross carbon fluxes, i.e. photosynthesis and respiration. The Gross Primary Productivity (GPP) simulated by different terrestrial models show large differences however, not only in terms of mean value but also in terms of phase and amplitude, thus hampering accurate investigations into carbon-climate feedbacks.

Recent measurements of a new atmospheric tracer, the Carbonyl sulphide (COS) open a window for evaluating and possibly optimizing the GPP of land surface models. The use of COS relies on the fact that it is absorbed by the leaves in a similar manner to CO2, while there seems to be nothing equivalent to respiration for COS. Following recent work by Launois et al. (ACP, 2015), there is a potential to evaluate model GPP from atmospheric COS and CO2 measurements, using a transport model and recent parameterizations for the non-photosynthetic sinks (oxic soils, atmospheric oxidation) and biogenic sources (oceans and anoxic soils) of COS. Vegetation uptake of COS is modeled as a linear function of GPP and the ratio of COS to CO2 rate of uptake by plants.

In this work, we investigate the strength of combining COS and CO2 data to evaluate the seasonal variations and the amplitude of the GPP simulated by an ensemble of land models, following the approach of Launois et al. (2015) based on the LMDz transport model. Forward transport simulations and inverse approaches where the monthly GPP and respiration fluxes are optimized to match the spatial and temporal gradient of COS and CO2 concentrations will be presented. The optimized GPP will be evaluated using Solar Induced Fluorescence (SIF) measurements from the GOME-2 product (Köhler et al., 2014) as independent diagnostic.

We will review the current strengths and weaknesses of the atmospheric COS measurements to provide new information on regional to continental GPP monthly mean estimates (especially in terms of phase and seasonal amplitude). We will further evaluate the COS-derived GPP values with independent estimated, such as those obtained from the FluxNet data base (flux driven estimates). Additionally we will use Solar Induced Fluorescence (SIF) measurements from GOME-2 satellite (Köhler et al., 2014) to evaluate the phase of the estimated GPP.

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Session 1: Combining multiple constrains

1e Using sun-induced fluorescence as additional constraint in a CO2 inversion

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The net uptake of CO_2 by the biosphere is the result of the imbalance between gross primary production (GPP) and terrestrial ecosystem respiration (TER), which are both large fluxes. GPP and TER individually respond to environmental drivers, and a better understanding of their responses is essential for future carbon-climate projections. Currently, the magnitude of GPP and TER as well as their response, particularly to droughts, are uncertain. A reason for this is that there are few direct measurements available of GPP and TER, while atmospheric CO_2 only constrains their sum (Net Ecosystem Exchange, NEE).

Recently, remotely sensed sun-induced fluorescence (SIF) emerged as a powerful proxy for photosynthesis on regional to global scale. Sun-induced fluorescence is the release of a fraction of light (~1% of the incoming light) from the chloroplast during photosynthesis. In particular, the Sun-Induced Fluorescence of Terrestrial Ecosystems Retrieval (SIFTER) product, that is retrieved from the GOME-2 instrument aboard the MetOp satellite, provides excellent coverage of SIF in the tropics, where the observations of atmospheric CO_2 mole fractions are sparse. SIFTER data is available for the period 2007-2016, encompassing the major droughts that have hit the Amazon in 2010 and 2015/2016. These years have shown exceptionally high growth rates of atmospheric CO_2 mole fractions, reflecting that changes in GPP and TER can affect the net CO_2 balance.

In our presentation we will demonstrate the use of SIFTER alongside the traditional atmospheric CO_2 constraint on NEE, within the CarbonTracker framework. We will explain how we used the spatiotemporal patterns within SIFTER to improve estimates of NEE, and show our first steps to separately estimate GPP and TER responses to large climate anomalies in the recent decade.

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Session 1: Combining multiple constrains

1f Atmospheric transport error: back to basics?

Paul Palmer

The scientific and political appetites for quantifying carbon (=CO_2 + CH_4) emissions are now aligned. On the global scale, as part of the Paris Agreement, countries are encouraged to use top-down methods to determine their nationally determined contributions to carbon emissions. Countries such as Switzerland and the UK have established national ground-based carbon measurement networks to determine top-down carbon emission inventories, and we are beginning to see measurement networks that are reporting carbon budgets from individual cities in Europe, US, and South Africa. There is an ongoing herculean effort associated with inter-calibration of carbon sensors that has resulted in significant reductions in systematic and random measurement errors. These improvements in carbon measurement technology and the corresponding errors has progressively increased the relative importance of characterizing atmospheric transport model error. As major international countries continue to invest billions of euros in space-based carbon measurement systems (e.g. Sentinel 7, GeoCarb, GOSAT-2) to address some of the biggest challenges we face this century, I argue that the modelling tools needed to translate those measurements into carbon emission estimates are not currently fit for that purpose.

TransCom has played a key role in characterizing transport model error using a range of numerical experiments, typically underpinned by sparse but accurate measurements (e.g. SF_6, CO_2). However, through no fault or criticism of TransCom, these activities are still many steps away from gaining fundamental insights into transport model error. I argue that a sustained and targeted measurement programme is necessary to achieve those insights that will help enable us to more accurately translate upcoming carbon measurements into carbon flux estimates. This programme would have to be coordinated with the NWP centres that provide the analyzed meteorological fields used by the atmospheric transport models.

The measurement programme should reflect the scientific goals of using the measurements. A programme that has an emphasis on the national scale (fluxes described on O(1000km)) will undoubtedly look different to one that is focused on the city-scale O(1km). Release of an atmospheric tracer is one approach that has been used in the past, but typically groups had used halogenated gases that are climatically relevant. Using such gases would be difficult to justify nowadays, even for the greater good. Studies have since relied on natural experiments associated with, for example, volcanic eruptions and gas leaks. The challenges we face are to find a chemically inert gas or particle that can be measured with an existing instrument that has a low limit of detection. Such as instrument would ideally provide vertical information (remotely) or directly via an aircraft. Some studies have argued for gases that are removed by the hydroxyl radical so that we can also use those data to provide constraints on the oxidizing capacity of the troposphere. I will review some of the possible candidates and put forward a strawman proposal for such a measurement programme.

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Session 2: Inversion Nuts and Bolts Session

2a Towards integrated tools for inversion studies: the Community Inversion Framework

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Atmospheric inversion approaches are expected to play a critical role in future observation-based monitoring systems for surface greenhouse gas (GHG) fluxes. In the past decade, the research community has developed various inversion softwares, mainly using variational or ensemble Bayesian optimization methods, with various assumptions on uncertainty structures and prior information and with various atmospheric chemistry-transport models. Each of them can assimilate some or all of the available observation streams for its domain area of interest: flask samples, in-situ measurements or satellite observations. Although referenced in peer-reviewed publications and usually accessible across the research community, most systems are not at the level of transparency, flexibility and accessibility needed to provide the scientific community and policy makers with a comprehensive and robust view of the uncertainties associated with the inverse estimation of GHG fluxes. Furthermore, their development, usually carried out by individual research institutes, may in the future not keep pace with the increasing scientific needs and technical possibilities. In the framework of the European H2020 project VERIFY, we are initiating a Community Inversion Framework (CIF) to help rationalize development efforts and leverage the strengths of individual inversion systems into a comprehensive framework.

The CIF will primarily be a protocol to allow various inversion bricks to be exchanged among researchers. In practice, the ensemble of bricks will make a flexible, transparent and open-source tool to estimate the fluxes of various GHGs both at global and regional scales. It will allow running different atmospheric transport models, different observation streams and different data assimilation approaches. This adaptability will allow a comprehensively assessment of uncertainty in a fully consistent framework.

We present here the main structure and functionalities of the system, as well as the community approach used for its development.

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Session 2: Inversion Nuts and Bolts

2b Fossil fuel CO2 flux constraint: The Vulcan and Hestia projects

Kevin Gurney, Jianming Liang, Risa Patarasuk, Maya Hutchins, Darragh O'Keeffe, Jianhua Huang, Thomas Lauvaux, Jocelyn Turnbull, Paul Shepson, Ben Ruddell, Okan Palu, Richard Rushforth, Ken Davis, James Whetstone, Riley Duren, AnnMarie Eldering, Charles Mi

The anthropogenic flux constraint to atmospheric inversion/assimilation systems remains a critical component in estimating GHG fluxes from atmospheric measurements. Research over the last ten years in the United States has generated new, high-resolution anthropogenic CO2 inventories using a combination of data mining, modeling, and numerical optimization. We will report on two nested efforts, the Vulcan Project aimed at the national scale and the Hestia Project, aimed at the urban scale. These new scientifically-based flux data products show considerable consistency to atmospheric observations in both forward and inverse approaches. Beyond use within the inversion/assimilation science, they are offering new ways to understand aspects of economic development, urbanization, and emissions mitigation policy at the sub-national scale. We will review a series of applications of the new data products to a spectrum of science and policy questions and outline next steps in inventory development.

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Session 2: Inversion Nuts and Bolts

2c Trade-offs between box models and 3D transport models

Stijn Naus, Maarten Krol, Sudanshu Pandey, Stephen Montzka

In the community of atmospheric modelling, it is commonly accepted that 3D chemistry and transport models (CTMs), in combination with atmospheric observations, are the most robust tools to use for e.g. improving constraints on emissions, or to advance our understanding of large-scale atmospheric chemistry. Of course, there are good reasons for this: 3D models represent the most comprehensive systems available, since all understanding of meteorology and chemistry can be explicitly included.

On the other hand, the use of simple box models in atmospheric research is also ubiquitous. Most recently, in two studies, constraints on the hydroxyl radical (OH) were derived in a relatively simple two-box model. Within the limitations of their model set-up (some of which are shared by CTMs), the studies found these constraints lacking. This inability to constrain OH, the main atmospheric oxidant, to the degree necessary for quantitative interpretation of pollutant budgets, in combination with its dominant role in atmospheric chemistry as a cleansing agent gives rise to important questions. Can a system as complex as that of OH be captured in a simple two-box model? And, how much is there to gain in the move from box models to more expensive and involving CTMs?

Here, we discuss and attempt to answer these questions. We do this by reducing the output from a three-tracer (methyl chloroform, methane and SF6) version of the 3D transport model TM5 to parametrizations that can be used in a two-box model. Through these parametrizations, we test common assumptions on parameters such as interhemispheric transport and stratospheric loss.

By testing the influence of different assumptions and parametrizations on the outcome of an inversion of a two-box model, we bring the analysis full-circle to recent studies, and we can quantitatively discuss the implications of our findings for past and future research.

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Session 2: Inversion Nuts and Bolts

2d New BFGS-based methods to accurately estimate a posterior error covariance matrix

Yosuke Niwa, Yosuke Fujii,

A four-dimensional variational method (4D-Var), one of prominent data assimilation/inverse methods, is attractive in that it estimates optimal model variables in a high-resolution without explicitly dealing with a model operator matrix whose size is too large to store in a memory or storage. However, a conventional 4D-Var does not estimate a posterior error covariance owing to its deterministic nature based on the maximum likelihood estimation. A posterior error covariance could provide valuable information not only of uncertainties of estimated variables but also of observational impacts, which is beneficial, for instance, for designing observation networks. In this study, we have developed two new methods to estimate a posterior error covariance matrix in a 4D-Var framework that employs a quasi-Newton method with Broyden-Fletcher-Goldfarb-Shanno (BFGS) algorithm. The developed two methods provide flexibility for the linearity of the model used. Even though the process treated by the model is theoretically linear, the model often has nonlinearity due to numerical issues. Originally, the quasi-Newton method allows some nonlinearity in an optimization and the first BFGS method inherits this advantage. On the other hand, the second BFGS method is limited in use with for an exactly linear case but is computationally more efficient. In order to accelerate the convergence speed of the estimation, both the methods are coupled with the ensemble approach. In this study, we evaluated performances of the new methods for an atmospheric CO2 inverse problem. The results showed that the developed methods can very accurately estimate the posterior error covariance matrix not only for the diagonal elements but also for the off-diagonal elements, whose estimation is usually a non-trivial task.

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Session 2: Inversion Nuts and Bolts

2e ODIAC in response to the TransCom and IG3IS objective(s)

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Since 2009, we have delivered ODIAC global high resolution fossil fuel CO2 emissions data to the community. ODIAC is based on disaggregation of country CDIAC estimates and their projection using BP. Unlike previous CDIAC gridded emission data, ODIAC carries emissions from international bunkers to complete the global picture of fossil fuel emissions. In response to an increased need for high-resolution CO2 simulations for satellite applications and city emission studies, we are working to improve the accuracy of emission disaggregation (e.g. new nightlight, more geospatial proxy and evaluation).

Currently none of existing gridded emissions are based on national emissions reported to UNFCCC. For example, EDGAR is closely following the IPCC emission inventory guideline (e.g. emission factors), but their estimates are not the same as the emissions submitted to UNFCCC. In response to the text in the meeting agenda, we propose to develop a version of ODIAC data using the UNFCCC emissions and present a plan for it. We also discuss the emission disaggregation that is important to map the reported emission on to model grids along with the FFCO2 uncertainty we've been studying.

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Session 2: Inversion Nuts and Bolts

2f Recent developpments in the LMDz Atmospheric Transport Model : impact on the CO2 simulated values and implications for inverse modeling

Marine Remaud, Frédéric Chevallier, Anne Cozic

The accuracy of CO2 surface fluxes inferred by inverse modeling heavily relies on the ability of Atmospheric Transport Models (ATM) to simulate atmospheric processes. The densification of surface networks and new satellite data put more pressure on the atmospheric modelling capabilities especially at regional scale where the transport errors are exacerbated. In order to fully benefit from theses new observations, forward modeling studies based on ATM are used to anticipate the ability of inverse systems to assimilate such new observations. However, the uncertainty of ATMs is usually hard to characterize while, when considering the differences between observations and simulations, ATM errors, errors in observations (for satellite retrievals) and errors in ATM surface boundary conditions (CO2 sources and sinks) are deeply entangled: this situation leaves much ambiguity and subjectivity in the interpretation. Further exploration of current atmospheric modelling capabilities is therefore heavily needed.

From that perspective, this study aims at benchmarking the sensitivity of the simulated atmospheric transport to the model assumptions and setups: the subgrid parameterization, the vertical resolution, horizontal resolution and wind forcing. We take the example of the global atmospheric transport model of the Laboratoire de Météorologie Dynamique (LMDz) guided by winds analyzed by numerical weather prediction centres. LMDz is part of the Earth system model of IPSL and is also used in the Copernicus Atmosphere Monitoring Service for operational CO2 atmospheric inversions. We consider the two reference versions of LMDz that participated to Climate Model Intercomparison Project (CMIP) versions (past) 4 and (ongoing) 6. The latter one benefits from many improvements compared to the former in terms of subgrid processes (convection, boundary layer mixing), radiation processes and vertical resolution in addition to other developments and tuning. Simulations using these two versions were run at several resolutions and driven by optimized CO2 surface fluxes. We also ran these two versions respectively with a dynamics nudged toward the ERA-Interim reanalysis (1998-2014) and nudged toward the ERA 5 reanalysis (2010-2016). We have compared the ensemble of simulations with a large dataset of independent (unassimilated) CO2 observations including satellite, TCCON retrievals and aircraft profiles. We show that the differences between the simulations of the CO2 column usually do not exceed 1 ppm. They affect the latitudinal gradient of the simulated column in a seasonal way that should impact the geographical distribution of the surface fluxes estimated by atmospheric inversions. We also show limited impact of higher vertical resolution compared to changes in physical paramaterizations. In spite of years of development of LMDz between CMIP4 and CMIP6, some known transport issues persist at the hourly scale or around the Inter-tropical convergence zone, which shows the importance of continued modelling effort by the scientific community for the exploitation of CO2 retrievals over the globe.

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Session 2: Inversion Nuts and Bolts

2g Hierarchical Bayesian trace gas flux inversions for big datasets using INLA and SPDEs

Luke Western, Matt Rigby, Anita Ganesan, Zhe Sha, Jonathan Rougier, Alistair Manning, Simon O'Doherty, Kieren Stanley, Dicken Young

Several recent developments in greenhouse gas observations and inverse methods are pushing the limits of traditional inverse frameworks: a) remote sensing platforms now provide orders of magnitude more data than were previously available; b) it is advantageous to solve for emissions at native model resolution, but with spatially and temporally correlated fluxes; and c) hierarchical Bayesian methods provide more robust uncertainty estimates than traditional frameworks in the presence of poorly specified prior and model uncertainties. Previous hierarchical Bayesian inverse modelling systems have used Markov Chain Monte Carlo (MCMC) to solve for some decomposition of the spatial field for relatively small datasets. However, these methods do not scale well for large datasets, or high-dimensional spatial and temporal fields. Recent advances in spatial statistics allow us to overcome these limitations in a computationally efficient framework. Continuous spatially correlated fields simplify when treated as a solution to a particular stochastic partial differential equation (SPDE), which results in a Gaussian field with spatial Markov properties. Propagating temporal, and spatio-temporal, information becomes possible by using a fast alternative to MCMC methods to perform hierarchical Bayesian inference, namely an integrated nested Laplacian approximation (INLA). These advances also pave the way for greenhouse gas inversions using very large data volumes that will be necessary when data from new Earth observation sensors become available. We demonstrate this method in a regional inversion by inferring spatial and spatio-temporally correlated UK methane emissions from tall tower measurements. Our results are comparable to recent MCMC inversions, but with a computational cost that is orders of magnitude smaller. I will discuss the strengths and weaknesses of this new technique for current and future inverse modelling endeavours.

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Session 2: Inversion Nuts and Bolts

2h The user interface

Phil DeCola

Session 3: Use of new data resources

3a The potential of a constellation of LEO satellite imagers to monitor worldwide fossil fuel CO_2 emissions from large cities and point sources

Franck Lespinas

Reducing the emissions of the greenhouse gases (GHG) is one of the most important environmental challenges of the 21st century to keep global warming below 2°C with respect to pre-industrial times. Meeting this objective will benefit from independent observation to accurately monitor GHG anthropogenic emissions at spatial scales relevant to carbon policy. In this context, satellites offer an unparalleled global spatial coverage since they can provide long-term, spatial high-resolution observations.

Here we present a new atmospheric inversion framework to provide a quantitative evaluation of the potential of future satellite XCO2 imagery to estimate anthropogenic emissions from point sources, cities, regions and countries OVER THE ENTIRE GLOBE. The Observing System Simulation Experiments (OSSE) focus on resolving CO2 emissions from groups of emitting pixels that form a XCO2 plume (clumps) using high spatial resolution space-borne imagery data, with a simple atmospheric transport (Gaussian). This version of the OSSE relies on realistic sampling of satellite data taking into account a single LEO imager, and constellations of up to four such imagers, but assumes no changes in XCO2 around clumps due to natural fluxes.

First results suggest that only fossil fuel CO2 emissions from clumps larger than 0.1 MtC yr-1 can be monitored by LEO imagers representing ESA's Sentinel CO2 planned missions. There is a significant positive impact of the number of satellites, and assuming shorter plumes decrease the performances of satellites.

Further work is needed in order to assess realism of the simulations through comparisons to detailed studies with more complex modeling framework for specific cities. There are also many ways to refine the OSSE through assessing the impact of swath, spatial resolution, precision, include vegetation fluxes, and spatial and temporal errors of clumps emissions. This system has the advantage to invert fluxes from pseudo data of satellite imagers at their native high resolution. It can therefore be applied to test the performances of other imagers like GEOCARB and OCO-3 and from constellations of different satellites.

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Session 3: Use of new data resources

3b Lessons and challenges learned from the NASA Carbon Monitoring System global flux inversion framework

Junjie Liu, Kevin Bowman, A. Anthony Bloom, Nick Parazoo, Meemong Lee, Dimitris Menemenlis, David Schimel

NASA Carbon Monitoring System (CMS) global flux inversion framework was launched around 2010, with the objective of using the full range of NASA satellite observations and modeling/analysis capabilities to quantify surface CO2 fluxes and the corresponding uncertainties. It consists of 4D-Var and ensemble Kalman filter flux inversion methods, GEOS-Chem forward and adjoint model, and bottom up fluxes (i.e., air-sea CO2 fluxes, terrestrial biosphere fluxes, and fossil fuel emissions) constrained by various satellite observations. The inversion system optimizes terrestrial biosphere and ocean carbon fluxes at monthly time scale by assimilating satellite CO2 observations from GOSAT and OCO-2. In combination with climate data, solar induced chlorophyll fluorescence (SIF) constrained GPP, and CO constrained biomass burning, we have quantified the impact of 2010 Amazonia drought, 2015-2016 El Nino, and two recent North American droughts on terrestrial biosphere CO2 fluxes. In this talk, I will summarize the scientific results learned so far from this framework, and further discuss the challenges of atmospheric flux inversion with satellite observations including posterior flux validation, observation bias, and spatiotemporally dependent observation coverage. In the end, I will discuss the possible future directions including quantifying and incorporating transport errors, online observation bias estimation, and high-resolution flux inversion.

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Session 3: Use of new data resources

3c A sector-level study of methane emissions from Brazil using satellite data

Rachel Tunnicliffe, Matthew Rigby, Anita Ganesan

When combined with the coverage of satellite data, the spatial distribution and seasonal variability of sources within Brazil make it an excellent case study for sector contributions to methane emissions.

Natural, wetland emissions are concentrated primarily on the Amazon river and in the western Pantanal region with biomass burning occurring in an 'arc of deforestation' around the Amazon rainforest border. Anthropogenic emissions are split between livestock in the south and central regions and fossil fuels and waste, centred around populated regions, on the Eastern coast. Furthermore, the emissions from wetlands are likely to peak within the wet season, whereas biomass burning will contribute more during the dry season.

Using column measurements from the Greenhouse Gases Observing Satellite (GOSAT) we constrain methane emissions for each sector across Brazil for 2015. Using high resolution modelling from the MetOffice Numerical Atmospheric Dispersion Model (NAME) to quantify the sensitivity of measured mol fractions to emissions, we apply a trans-dimensional hierarchical Markov Chain Monte Carlo (MCMC) Bayesian approach to characterise the emission magnitudes and, crucially, the uncertainties (Ganesan et al, 2014; Lunt et al, 2016) based on prior emissions maps for all the major methane sources. The nature of this study also allows us to quantify anthropogenic emissions from Brazil presenting the opportunity for comparison with UNFCCC reporting.

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Session 3: Use of new data resources

3d How can we optimize GHGs monitoring for regional inversion modelling

Ingeborg Levin, Ute Karstens

A network of (tall) tower stations has been installed in the framework of ICOS RI (Integrated Carbon Observation System Research Infrastructure) with the aim of in situ monitoring of greenhouse gases (GHG) and associated tracer concentrations over the European continent. Following the ICOS Atmospheric Station Specifications, measurements are performed at 3-5 height levels, depending on the height of the tower, where the ground-based analysis system is frequently switching between the different heights in order to gain vertical profile information. To monitor atmospheric constituents, which can currently only be measured in dedicated laboratories, such as isotopes in CO2 and CH4, in situ observations are supplemented by flask sampling. Flask sampling is, however, possible only at one height level, and in order to use respective results for quality control of the in situ observations, integrated flask sampling, e.g. over 30-60 minutes during the afternoon is preferred. This sampling strategy would fit to the still existing limitation of inverse models to only ingest afternoon data. However, representative and precise gradient measurements can only be obtained with more frequent switching between levels, e.g. every 5 minutes. The experimentalists' question now arises, what would be the optimal sampling strategy at tall tower stations, to allow regular quality control and, at the same time, deliver representative vertical profiles during the afternoon. Do regional inverse models use the (daytime) profile information at all? If not, what would be the preferred height level for the inversions (this would then also be the level where flasks will be collected)? Observations from the first labelled ICOS stations will be presented and the issue discussed with the TRANSCOM modelling community in order to best serve their needs.

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Session 3: Use of new data resources

3e Exploring the observational variability and constraint of in-situ data in the Northeastern US for future CO_2 flux estimation

K. Mueller, S. Gourdji, I. Lopez-Coto, A. Karion, S. Ghosh, J. Whetstone

This work investigates the variability in both urban and extra-urban in-situ CO2 observations located in the Northeastern portion of the United States with a particular focus on the metropolitan areas of Washington DC and Baltimore. These observations will ultimately be used to estimate CO2 sources and sinks using an inversion framework for November 2016 to October 2017. The study uses tower-based continuous in-situ CO2 observations from 37 sites within the regional domain including a dense network of urban tower sites that underpin the National Institute for Standards and Technology (NIST) Northeast Corridor-Baltimore/Washington (NEC-B/W) project. The research explores statistical methods to discern which components (e.g. sources and sinks, meteorology, incoming flows of CO2 - aka 'background') influence the variability of the observational signals at different times for various types of locations. In-situ CO2 mole fraction measurements from February through September are used in conjunction with the WRF-STILT transport and dispersion model. To better understand the observational variability, the tower sites are classified by landuse type and the mole fraction time-series from these types of towers are regressed against anthropogenic emission priors (e.g. Vulcan, FFDAS, ACES, etc.), biological fluxes (e.g. VPRM), background representations (e.g. from global models such as NOAA's Carbon Tracker, from observations at the edge of the analysis domain, etc.), meteorology (both near field and far field from WRF-STILT), etc. The regression is conducted for each month, to ascertain monthly averages, as well along a moving window to see how the regression coefficients change with time. Finally, the research involves estimating the statistical leverage of the observations to determine which observation(s) can be highly influential on inversion estimates. Results from this analysis will help us better understand observational constraints of the inversion framework and provide a priori knowledge of which factors and observations have greatest influence on emission estimates at different time periods. Such insight is particularly important for metropolitan areas like the Northeastern US that cannot be easily disentangled, are downwind of large emission sources, contain emissions that are generally disperse (mainly from traffic), and experience variable coastal meteorology (e.g. from various bays and the Atlantic Ocean).

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Session 4: Local sources and high resolutions

4a National scale CO2 inverse modelling: a New Zealand case study

Sara E. Mikaloff Fletcher, Kay Steinkamp, Gordon Brailsford, Dan Smale, Zoe Buxton, Peter Sperlich, Stuart Moore, Elizabeth D. Keller, W. Troy Baisden, and Britton B. Stephens

Atmospheric observations of CO2 and other greenhouse gases have the potential to constrain estimates of terrestrial and oceanic CO2 fluxes through atmospheric inverse modelling. Yet, applying these methods at national scale to verify and improve the National Inventory Report (NIR) and support the Paris agreement remains at the frontier of CO2 science. We will present results from a national CO2 atmospheric inverse model developed for New Zealand, as a case study.

Our inverse approach infers net air-sea and air-land CO2 fluxes from measurement records, using back-trajectory simulations from the Numerical Atmospheric dispersion Modelling Environment (NAME) Lagrangian dispersion model, driven by meteorology from the New Zealand Limited Area

Model (NZLAM) weather prediction model, which is run at 0.1° (10-12 km) resolution. Our first results are based on in situ measurements from two fixed sites, Baring Head on the southern tip of New Zealand's North Island (41.41°S, 174.87°E) and Lauder from the central South Island (45.034°S, 169.68°E), and ship board data from monthly cruises between Japan, New Zealand, and Australia. We also show results that include our newest site, Maunga Kakaramea in the central North Island (38.33°S, 176.38°E) for the period when data is available for all three in situ sites (2012-2017). A range of scenarios is used to assess the sensitivity of the inversion method to underlying assumptions and to ensure robustness of the results.

We find that the National Inventory Report may under-estimate New Zealand's land carbon uptake by 30-60%, when differences between the total uptake observed by the atmosphere and accounting rules of the NIR are considered. Much of this additional uptake occurs in the southwest of New Zealand's South Island, an unihabited region dominated by indigenous forests. First analysis of 13C isotope ratios in CO2 confirms the presence of a vigorous land-based carbon sink in this region. This carbon sink is characterised by strong interannual variability, and suggests an unexpectedly strong response of New Zealand's land carbon sink to drought stress. Observations from our newest observing site in the central North Island shed new light on carbon fluxes in this subtropical region.

In addition to addressing the scientific findings of this study, we will discuss the process used to engage New Zealand's NIR and environmental policy communities, starting from the development phase of the project. This will include the strategies used to resolve differences between components of the carbon budget counted in the NIR and those detected by the inversion, communicate uncertainties, and plan research activities that meet policy needs.

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Session 4: Local sources and high resolutions

4b Difficulties in inverse modelling of radioactivity point releases

Petra Seibert

Point releases of radioactivity may occur in the context of nuclear accidents and nuclear weapon tests. Determining location and temporal release patterns by inverse modelling is fraught with distinct difficulties. These include the proper formulation of the cost function in the case of many zero measurements, the detection threshold (there is no real zero measurement), the non-Gaussian pdf of the data, and the issue of localised plumes and and near hits/misses at observation sites, which is another cost function issue. Also, often information is quite sparse. Some of these topics are also relevant for other types of sources. Problems will be explained, possible solutions sketched, and examples shown.

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Session 4: Local sources and high resolutions

4c **Estimates of regional CH_4 emissions in the Surat Basin, Queensland, Australia from in situ measurements and atmospheric inversion**

Zoë Loh, David Etheridge, Ashok Luhar, Julie Noonan

The Surat Basin in Central Queensland, Australia is an area of rapidly expanding Coal Seam Gas (CSG) production. Other known sources of methane in the area include agriculture (principally from beef production), power stations, coal mining, landfills and wastewater treatment, domestic wood heating, geological seepage and intermittent biomass burning.

We have established a pair of well-intercalibrated monitoring stations measuring methane continuously, along with carbon dioxide (and carbon monoxide at the site most likely to be impacted by biomass burning emissions from a proximate forested area) (Picarro G2301 and G2401 analysers) as well as meteorological data. The two stations have been positioned based on prevailing wind direction, to maximise the amount of time one site sees a parcel of 'background' air arriving at the Surat Basin and the other sees that same parcel of air after it has traversed an area of increasingly intense CSG activity. We have also overseen the production of a regional scale 'bottom up' inventory of methane emissions from the Surat Basin, excluding emissions from CSG and biomass burning.

Using a regional scale modelling approach (CSIRO's The Air Pollution Model (TAPM vn4.0.4) Hurley et al., 2005), run in an inverse sense and coupled to a Bayesian inference framework utilising the inventory data as a prior, we have used the atmospheric concentration data to constrain methane emissions estimates.

Here we will present our latest results from this project, with emphasis on the choice of background concentration to use in regional scale inversion modelling studies and the balance between the uncertainties assigned to the prior and the observations, in determining the inversion result.

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Session 4: Local sources and high resolutions

4d Trend detection of urban GHG emissions from ground-based and satellite observing systems

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The Indianapolis Flux (INFLUX) Experiment has collected an unprecedented volume of atmospheric greenhouse gas measurements across the Indianapolis metropolitan area from aircraft, remote-sensing, and tower-based observational platforms. Assimilated in a high-resolution urban inversion system, atmospheric data provide an independent constraint to existing emission products, directly supporting the integration of economic data into urban emission systems. We present here the first multi-year assessment of carbon dioxide (CO2), methane (CH4), and carbon monoxide (CO) emissions from anthropogenic activities in comparison to multiple bottom-up emission products. Biogenic CO2 fluxes are quantified using an optimized biogeochemical model at high resolution, further refined within the atmospheric inversion system. We also present the first sector-based inversion by jointly assimilating CO2 and CO mixing ratios to quantify the dominant sectors of emissions over the entire period (2012-2015). We show here how the combination of information sources supports the evaluation of mitigation policies and helps development of understanding regarding the mechanisms driving emission trends at the level of economical sectors.

A similar approach can be applied to the largest 60 metropolitan areas across the world, with an evaluation of the method over five major urban centers assimilating selected tracks from the Orbiting Carbon Observatory (OCO)-2 mission. Different climatic conditions and urban environments provide key information to diagnose the major sources of uncertainties in future satellite-based inversion systems. We present an estimate of long-term trend detection using remote-sensing data and discuss optimal observing design strategies for future satellite missions.

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Session 4: Local sources and high resolutions

4e Top-down Validation of Swiss non-CO_2 Greenhouse Gas Emissions

Stephan Henne, Joachim Mohn, Markus Leuenberger, Frank Meinhardt, Martin Steinbacher, Martin K. Vollmer, Stefan Reimann, Lukas Emmenegger, Dominik Brunner

Globally, emissions of long-lived non-CO_2 greenhouse gases (GHG; methane, nitrous oxide and halogenated compounds) account for approximately 30 % of the radiative forcing of all anthropogenic GHG emissions. However, on the country level 'bottom-up' estimates of anthropogenic non-CO_2 GHGs are often connected with relatively large uncertainties when compared with those of anthropogenic CO_2. The latter can be fairly well established from (fossil) fuel statistics, whereas the former originate from a multitude of rather diffuse sources for which both activity data and emission factors carry substantial uncertainties. For example, the Swiss national inventory report (NIR) to UNFCCC gives an uncertainty of 39.5 % and 18 % for N_2O and CH_4 emissions, respectively, whereas that of anthropogenic CO_2 is given as 0.7 %. In order to validate national inventories and ascertain that target emission reductions can be reached with a given set of reduction measures, it is indispensable to apply independent 'top-down' methods (i.e., atmospheric inversions) on the country scale.

Here, we present regional-scale (~300 x 200 km^2) atmospheric inversion studies for non-CO_2 GHG emission estimates in Switzerland, making use of observations on the Swiss Plateau as well as the neighbouring mountain-top sites Jungfraujoch (JFJ) and Schauinsland (SSL, Germany). Continuous CH_4 observations are available since 2013, whereas continuous observations of N_2O commenced at the tall tower site (Beromünster) in January 2017. In addition, the mountain-top sites have been providing continuous CH_4, N_2O, and halocarbon (JFJ only) observations for several years.

We use a high-resolution (7 x 7 km^2) Lagrangian particle dispersion model (FLEXPART-COSMO) in connection with two different inversion systems (Bayesian and extended Kalman filter) to estimate spatially and temporally resolved emissions for the Swiss domain. In general, we find good agreement of the total Swiss CH_4 emissions between our 'top-down' estimate and the NIR 'bottom-up' reporting. In addition, a robust emission seasonality, with reduced winter time values, can be seen in all years. We observe that uncertainties in the model's boundary conditions can induce large offsets in the national total emissions. However, spatial emission patterns are less sensitive to the choice of boundary conditions. For N_2O we present first preliminary inverse modelling results making use of the most recent measurements at the tall tower site and compare the results to the Swiss NIR. For halocarbons we discuss emission estimates for the most important hydrofluorocarbons (HFCs) on the European and Swiss scale, again comparing these estimates to those officially reported to UNFCCC.

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Session 4: Local sources and high resolutions

4f Global inverse modeling of methane emissions with high resolution transport model based on ground-based monitoring and GOSAT satellite retrievals

Shamil Maksyutov, Aki Tsuruta, Rajesh Janardanan, Akihiko Ito, Johannes Kaiser, Greet Janssens-Maenhout, Ed Dlugokencky, Motoki Sasakawa, Yukio Yoshida, Tsuneo Matsunaga

We perform a global high-resolution methane flux inversion based on a Lagrangian-Eulerian coupled tracer transport model to estimate global methane emissions using atmospheric methane data collected at global in-situ network, which is archived at WDCGG, and GOSAT satellite retrievals. For better accounting of anthropogenic emissions localized around large cities, we use the Lagrangian particle dispersion model FLEXPART to model local tracer transport at 0.1° spatial resolution. FLEXPART is coupled to a global atmospheric tracer transport model (NIES-TM). The adjoint of the coupled transport model is used in an iterative optimization procedure. High-resolution prior fluxes were prepared for anthropogenic emissions (EDGAR), biomass burning (GFAS), and wetlands (VISIT). High resolution wetland emission dataset was constructed using a 0.5° monthly emission data simulated by VISIT model and wetland area fraction map by Global Lake and Wetlands Database (GLWD). The inverse model optimizes corrections to two categories of fluxes: anthropogenic and natural (wetlands). Biweekly methane emissions at high spatial resolution are estimated for 2009 to 2012. The inverse model optimizes a fit to the ground-based observations around the globe. Notably, the coupled transport model manages to better reproduce ground based continuous observations in mid- and high-latitudes in winter, due to resolving both anthropogenic emission plumes and near-surface transport in the shallow boundary layer. Forward simulation with surface fluxes optimized by assimilating ground-based observations is used to reduce the mismatch with GOSAT Level 2 XCH_4 data. The monthly mean difference between GOSAT data and the optimized forward simulation is estimated for each 10°x10° latitude-longitude box is subtracted from GOSAT retrievals before including them in the inversion. Inverse modeling combining ground-based observations and GOSAT retrievals show the bias correction scheme is successful in retaining a good fit to the ground-based observations. The suggested correction removes large scale biases in GOSAT retrievals with respect to the model simulation, while retaining local scale variability that contains most information on anthropogenic emissions, so it favors information on localized high emissions of anthropogenic origin over large scale atmospheric signals from natural fluxes.

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Session 4: Local sources and high resolutions

4g Assessment of atmospheric carbon dioxide variations over the Seoul capital area from space

Chaerin Park, Su-Jong Jeong

Assessment of urban carbon emission is a critical issue to understand the global carbon cycle. In this research, we evaluate the spatial and temporal variations in urban carbon dioxide over the Seoul Capital Area, where is one of apparent Megacities across the world, by analyzing column integrated XCO2 from Orbiting Carbon Observatory-2 from 2014 to 2018. Results show that Seoul has higher values of carbon dioxide concentration than its neighbor background value. The urban enhancement of carbon dioxide varies with season. More details in our study will be presented in the workshop. Our Carbon dioxide anomaly statistics and distribution of Seoul can provide valuable insight for comprehending carbon dioxide emissions over the megacity across the world.

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Session 5: Posters session

Posters session will be in the meeting room.

For poster abstracts see after session 6 abstracts

Session 6: Inversion synthesis

6a EUROCOM: intercomparison of European scale atmospheric inversions of the CO_2 terrestrial ecosystem fluxes

G. Broquet, M. Scholze, U. Karstens, G. Monteil, M. Lang, P. Peylin, R. Thompson, C. Gerbig, F.-T. Koch, I. Van der Lann-Luijkx, W. Peters, E. White, M. Rigby, A. Meesters, H. Dolman, A. Vermeulen, F. Chevallier, P. Ciais, I. Pison, J. Tarniewic, L. Rivie

The EUROCOM project aims at providing a robust, inverse-modeling based estimate of the CO2 ecosystem fluxes over 10 recent years: 2006-2015, and of the associated uncertainties. There is still a large spread between the estimates of the net CO2 fluxes from terrestrial ecosystems at continental to regional scales either from bottom-up ecosystem models or from atmospheric inversions. The current estimates from global coarse-grid inversions of the net CO2 flux from the European ecosystems during the last decade range from a small source to a sink of more than 1PgC/yr (Peylin et al., 2013; Chevallier et al., 2014; Reuter et al., 2017). The resulting uncertainty hampers our ability to forecast their evolution. It also limits our ability to verify the impact of policies for the increase of the natural carbon uptake, e.g., those pledged by countries in the context of the Paris agreement.

However, a relatively dense network of ground based atmospheric CO2 measurement sites has been deployed in Europe for more than 15 years. Furthermore, a group of mesoscale systems for the atmospheric inversion of the CO2 European fluxes has emerged in recent years. Such systems are expected to better exploit dense atmospheric measurement networks and thus to provide improved estimates of the CO2 fluxes at the continental scale compared to global inversions, as well as providing reliable estimates at subcontinental scales. Finally, inter-comparisons of global scale inversions, in particular in the frame of TRANSCOM, have helped diagnose the robustness of large-scale CO2 flux estimates and the range of uncertainties. They have also helped improve the inverse modeling frameworks.

In this context, EUROCOM has led an intercomparison of state of the art European scale CO2 atmospheric inversions assimilating ground-based in-situ CO2 measurements. This is achieved through an international collaborative effort, involving seven of the European leading institutes in the field of the atmospheric inversions and the support from many data providers. It follows a harmonized protocol to ensure comparability between various results and allow a synthesis of the most robust and uncertain patterns arising from the current atmospheric inversion frameworks. In particular, inversions use a common selection of observation sites (including sites that are now included in ICOS), a common fossil-fuel emissions inventory (derived from EDGAR4.3) and a similar half-degree inverse modeling grid. The inversions differ by their prior estimate of the ecosystem fluxes (from ecosystem models such as VPRM, LPJ-GUESS, SiBCASA and ORCHIDEE), by their transport models (FLEXPART, STILT, NAME, TM5 and CHIMERE), and by their inversion algorithms (variational, EnKF and MCMC).

This presentation provides an overview of the main scientific and technical outcomes of the inter-comparison, and discusses the future of the inter-comparison and of the collaboration.

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Session 6: Inversion synthesis

6b Interannual variations of terrestrial CO2 fluxes 1957-2016 and their relation to climate variations

Christian Rödenbeck, Sönke Zaehle, Ralph Keeling, and Martin Heimann

The response of the terrestrial Net Ecosystem Exchange (NEE) of CO2 to climate variations and trends may crucially determine the future climate trajectory.

To understand this response and its effect on multi-decadal trends, NEE time series as long as possible are essential. Atmospheric CO2 observations started in 1957 and the following years at a small number of stations.

By combining these early data into a "quasi-homogeneous" set, they can be used in an atmospheric inversion to constrain interannual NEE variations at least over large spatial scales. As in the later decades, we find tropical NEE anomalies during El Niño events, and northern extratropical anomalies a few months later.

In order to directly quantify the relationship of NEE variations to climate variations on interannual time scales, we built a linear regression of interannual NEE anomalies against observed air temperature anomalies into the atmospheric inverse calculation. This allows us to estimate the sensitivity of NEE to interannual variations in temperature (seen as climate proxy) resolved in space and with season. As this sensitivity comprises both direct temperature effects and effects of other climate variables co-varying with temperature, we interpret it as `"interannual climate sensitivity'".

We find distinct seasonal patterns of this sensitivity in the northern extratropics, that are consistent with the expected seasonal responses of photosynthesis, respiration, and fire. Within uncertainties, these sensitivity patterns are consistent with independent inferrences from eddy covariance data.

On large spatial scales, northern extratropical as well as tropical interannual NEE variations inferred from the NEE-T regression reproduce well the estimates of an atmospheric inversion with explicit interannual degrees of freedom. The results thus can also be used to gap-fill or extrapolate observational records, or to separate interannual variations from longer-term trends.

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Session 6: Inversion synthesis

6c The OCO 2 Model Intercomparison Project Reveals Systematic Transport Model Effects on Inverse Model CO_2 Fluxes

Andrew Schuh, Andrew R. Jacobson, Sourish Basu, Brad Weir, David F. Baker, Kevin Bowman, Frédéric Chevallier, Sean Crowell, Ken Davis, Feng Deng, A. Scott Denning, Liang Feng, Dylan B. Jones, Junjie Liu, Paul Palmer

The NASA Orbiting Carbon Observatory 2 program has organized an atmospheric inverse model intercomparison activity, in which modeling groups have performed experiments assimilating OCO 2 retrievals and traditional in situ CO2 measurements. This collection of inverse models is dominated by atmospheric transport simulated by just two models: three use TM5 and four use GEOS Chem. Forward simulations of CO2 and SF6 in these two models reveal systematic differences in vertical meridional transport, suggesting that GEOS Chem moves tracer mass out of northern midlatitudes more quickly than TM5. In an inverse model framework, the ensemble of GEOS Chem models retrieves a larger annual cycle of surface CO2 fluxes in the large zonal band from the equator to 45°N. Since inverse models frequently simulate a net land sink by amplifying the annual cycle of prior models, one might expect that GEOS Chem would have a larger net sink in this latitude range, but we find the opposite. The differences between the two models in seasonality and long term mean fluxes are reversed north of 45°N. We provide potential explanations for these flux differences, and link them to transport processes using SF6 constraints.

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Session 6: Inversion synthesis

6d GOSAT CO_2 Inversion Inter-comparison Experiment Phase-2: interim progress report

Hiroshi Takagi, Sander Houweling, Shamil Maksyutov, David Baker, Frédéric Chevallier, Feng Deng, Liang Feng, Fei Jiang, and participating modelers

Atmospheric inversion techniques have been utilized for estimating the space-time distribution of GHG surface fluxes in gaining insight into how anthropogenic activities modify the stocks and flows of carbon over the globe. To make further progress in the effort, it is essential to evaluate, quantify, and subsequently reduce the uncertainties in the flux estimation process. Inter-comparisons of existing atmospheric inversion systems as well as their components provide the opportunity to investigate the uncertainties. In the late 1990s, the TransCom model inter-comparison studies assessed the role of transport model uncertainties in flux estimation, and more recently, after the advent of satellites dedicated to GHG monitoring, the GOSAT inversion inter-comparison (Phase-I) evaluated the full uncertainty of GOSAT-based CO_2 flux estimation by allowing the study participants to use the inversion system, a priori flux dataset, surface CO_2 observation dataset, and GOSAT column-mean CO_2 (X_{CO2}) retrieval dataset of their choice.

Here, in the second phase of the GOSAT inversion inter-comparison, we explore differences among the existing inversion systems and evaluate their contribution to the uncertainties of flux estimates. For this, the participants used a common input dataset that consists of an a priori flux dataset, GOSAT X_{CO2} retrieval dataset, and a surface CO_2 observation dataset. A common criterion for observation data filtering was also specified. The second phase study takes advantage of a 5-year-long analysis period (2009-2014) during which GOSAT X_{CO2} retrievals are continually available, to assess the robustness of inversion-derived estimates of the impact of major weather anomalies on carbon fluxes. We contrast and characterize fluxes that are estimated from satellite and surface CO_2 data combined, satellite data only, and surface data only, respectively. Our latest results are presented.

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Session 6: Inversion synthesis

6e Top-down estimates of N2O emissions over the past two decades

R. L. Thompson, K. Wells, C. Wilson, A. Gressent, E. Koffi, D. Millet, M. Prather, H. Tian, P. Suntharalingam and J. G. Canadell

Nitrous oxide (N_2O) is the third most important long-lived greenhouse gas and contributes 0.17 Wm^{-2} (6%) to radiative forcing according to IPCC AR5. Atmospheric mixing ratios of N_2O have increased by approximately 20% since the pre-industrial era largely due to the human perturbation of the N-cycle. This has occurred by increasing the abundance of reactive nitrogen in the environment, especially through the use of N-fertilizers, which has led to greater emissions of N_2O. Owing to the importance of N_2O as a greenhouse gas, but also as an ozone depleting substance, the Global Carbon Project is preparing the first full N_2O budget. Similar to CO_2 and CH_4 budgets, the N_2O budget incorporates bottom-up and top-down modelling studies to cover all sources of N_2O as well as its atmospheric loss.

Here we present the results of the top-down component of the budget, which included five global inverse models. The inversions were run with the user's own choice of input data and settings for the minimum period of 1995 to 2014. The model results were assessed by comparisons to independent observations and by using a number of diagnostics such as the atmospheric lifetime and the loss of N_2O. One model was found to be a considerable outlier and was thus excluded from the ensemble statistics. Posterior emissions were analysed at global and regional scales and compared to the independent bottom-up modelling studies. We find broad consistency among the inversions for the global total emission of 16-18 TgN/y and with land ecosystem models for the total land emissions of approximately 10 TgN/y. On the other hand, the inversions find larger ocean emissions, of 6-7 TgN/y, compared to the range of ocean biogeochemistry models of 3-4 TgN/y. The inversions differed considerably, however, in the allocation of land emissions at continental scale, particularly in the tropics and the Southern Hemisphere extra-tropics, which are poorly constrained by observations.

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Session 6: Inversion synthesis

6.f Atmospheric inversions in the Global Carbon Budget

Ingrid van der Laan-Luijkx, Christian Rödenbeck, Frédéric Chevallier, Corinne Le Quéré, Philippe Ciais, Wouter Peters

The Global Carbon Project's Carbon Budget 2017 (Le Quéré, et al. 2018) is the most recent update on the global carbon emissions and carbon sinks and their trends. The major components included in the budget are: emissions from fossil fuel combustion and industry, emissions from land-use change, the growth rate of the atmospheric CO2 concentration, and the land and ocean sinks. The results are based on observations, statistics and model estimates. The atmospheric perspective is also included with the results from three inverse methods that are updated annually. These are Jena CarboScope (Rödenbeck, 2005), CAMS (Chevallier et al., 2005), and CarbonTracker Europe (van der Laan-Luijkx et al. 2017). The analysis focuses on two aspects: (a) the derivation of the year-to-year changes in total land fluxes, and (b) the spatial breakdown of combined land and ocean fluxes between the Northern Hemisphere, Tropics and Southern Hemisphere.

In the next update of the Global Carbon Budget we will extend the inverse results to cover the carbon fluxes up to the end of 2017. These preliminary results will be shown at the conference. We will show an extended comparison between these three atmospheric inversions, and further study the differences between their estimated fluxes. At the conference we will show the differences in approach, and the choices in the prior fluxes including the fossil fuel emissions and its variability. We will compare the results from the three inversions and focus on the ocean-land distribution of the carbon sinks, the spatial variability, including a regional assessment for the fluxes in TransCom/RECCAP-II regions, and we will compare the simulated CO2 concentrations to observed time series from the global network.

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Session 6: Inversion synthesis

6g Top-down constraints on the North American carbon cycle from the first decade of the North American Carbon Program

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The North American atmospheric carbon measurement network has grown from a handful of sites in 2004 to more than 100 sites in 2017, thanks to the combined efforts of US agencies contributing to the North American Carbon Program, Environment and Climate Change Canada, and private investment in GHG monitoring. This unprecedented dataset informs spatially and temporally resolved emissions and uptake flux estimates and provides quantitative information about drivers of variability, such as rainfall and temperature. Recent advances in regional transport modeling and the development of flexible, high-resolution, inversion methods enable flux estimation at scales that are sufficiently fine to reduce the impact of aggregation errors and to linking inferred flux variability to underlying drivers. CarbonTracker-Lagrange (CT-L) is a flexible modeling framework that leverages these model developments and provides a platform for systematic comparison of data assimilation techniques and evaluation of assumed prior, model and observation errors. CT-L uses footprints from the WRF-STILT modeling system to relate atmospheric measurements to upwind fluxes and boundary values. Fluxes are adjusted using Bayesian or Geostatistical methods to provide optimal agreement with available observations. Footprints are pre-computed and the optimization algorithms are efficient. Thus, it is possible to explore a wide range of inversion scenarios designed to investigate sensitivity to model inadequacies, including errors in simulated atmospheric transport and boundary values, and to the mathematical construct of the optimization and various data weighting strategies. Multi-species data inform flux estimation by providing additional constraints to enable source/sink attribution. We are working to implement multi-species inversions for CO_2 flux estimation using CO_2 data along with $\delta^{13}CO_2$, COS and radiocarbon observations and for CH_4 flux estimation using data for various hydrocarbons. We will present a synthesis of North American CO_2 and CH_4 surface flux estimates spanning nearly a decade and with rigorously quantified uncertainties.

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Poster session

P1 CarbonTracker Europe-CH4 Data Assimilation System for global and regional methane emission estimations

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Carbon Tracker Data Assimilation System was developed in NOAA/ESRL and further in Wageningen University and has been applied in various greenhouse gas budget studies. We present a model version with developments for methane and methane 13C isotope for studying the anthropogenic and natural methane emissions. Carbon Tracker Europe-CH4 (CTE-CH4) uses TM5 model for atmospheric transport with adjusted zoom regions for Europe and high northern latitudes and Ensemble Kalman filter method for concentration data assimilation. Methane loss in atmosphere is included with contributions from tropospheric and stratospheric OH, Cl and O(1D) sink. Prior emissions are described for anthropogenic (EDGAR), natural (LPX-Bern), ocean, termite and fire (GFED) sources, and for the 13C isotope separately for non-biogenic and biogenic proportion in anthropogenic sources. CTE-CH4 has been applied for the global methane budget, regionally in 1x1 resolution for Finland+Scandinavia, and it has the capability for assimilating satellite column measurements. The temporal resolution of the fluxes is one week, and the current simulations extend from year 2000 to 2015.

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Poster session

P2 Transport model uncertainty associated with model resolution

Anna Agusti-Panareda

Transport errors depend on the parameterization of advection, convection and turbulent mixing processes, as well as errors in the meteorological analysis and errors associated with spatial and temporal discretization in the model. In this poster we will show the impact of increasing the spatial resolution on the root mean square errors of simulated atmospheric CO2 for a winter month and a summer month. Simulations of atmospheric CO2 are performed with the Integrated Forecasting System (IFS) model at the European Centre for Medium Range Weather Forecast (ECMWF) with a range of resolutions from 80 km (ERA-Interim resolution) to 9 km (ECMWF Numerical Weather Prediction resolution). The transport errors are computed for the daily mean, minimum and maximum values using a wide range of CO2 observations over the globe. Results show that the high resolution consistently leads to smaller transport errors compared to independent observations in winter, but in summer the results are mixed, with high resolution simulations highlighting errors associated with local transport and local influence of surface CO2 fluxes. The overall reduction in the transport errors in the high resolution simulations is linked to improved winds and a reduction in the representativity errors associated with better topography and land-sea mask. Thus, the largest improvements can be seen over mountains and coastal sites.

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Poster session

P3 Using joint satellite and isotopic CH4 measurements to constrain uncertainty on the evolution of the global CH4 budget.

A. Anthony Bloom, John Worden, Yi Yin, Christian Frankenberg, Joannes Maasakkers, Daniel Jacob, Sudhanshu Pandey

Major uncertainties persist in the current understanding of the global methane (CH4) budget. The primary sources of ambiguity in global CH4 source and sink estimates - and the attribution of the growth rate to underlying source and sink processes - include the confounding roles of transport and chemistry errors, prior budget assumptions, and uncertainties in sector-specific isotopic CH4 fractions. Here, we produce a first continental-scale and sector-specific estimate of the global CH4 budget constrained simultaneously by atmospheric CH4 and CO inversion results, surface-based measurement of the total and isotopic CH4 budgets and all available uncertainty characteristics. Through a Bayesian formulation of the global CH4 source and sink attribution problem, we retrieve a robust estimate of the uncertainty in the partitioning of the atmospheric CH4 burden, and we identify the missing constraints required to improve statistical confidence in hypothesized CH4 budget trends. Finally, we also investigate the potential role of recent lower-tropospheric CH4 column retrieval constraints on the global CH4 budget estimation.

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Poster session

P4 MicroCarb, a new satellite for atmospheric CO2 monitoring

Francois-Marie Bréon, for the MicroCarb science team

MicroCarb is a spaceborne instrument under development at the French space agency for a launch in 2021. It shares several feature with the currently flying OCO-2 but with an innovative optical design that may make it less prone to measurement biases. In addition, it caries an additional spectral band at 1.27 µm that, although contaminated by airglow, may prove useful for a correction of aerosol scattering. The instrument is light and compact, so that it may be carried onboard platforms of opportunities for a continuous and dense observation of the atmospheric CO2.

The poster will present the scientific objectives of MicroCarb, its design with a focus on the original features of this CO2 monitoring mission.

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Poster session

P5 Atmospheric methane (CH_4) budget and variability during 1984-2017

Naveen Chandra, Prabir K. Patra, Akihiko Ito, Masayuki Takigawa, and Shingo Watanabe

The contributions of various methane source types to CH_4 growth rate variabilities over the past 4 decades (1980s-2010s) remained puzzling to the research community (e.g., Patra et al., 2016). The budget of CH_4, which depends on the tools of estimation, is also greatly uncertain (Saunois et al., 2016). For example, the chemistry-transport model properties play key role in determining the emission and loss budgets from atmospheric data. We first show the recent developments in our MIROC4.0 atmospheric general circulation model (AGCM)-based CTM (MIROC4-ACTM; Patra et al., revised, 2018). The model transport is validated using SF_6 from aircraft measurements in the troposphere (Wofsy et al., 2011) and balloon-borne measurements in the stratosphere (Ray et al., 2017, Goto et al., 2017). Further the chemistry in the model is evaluated using CH_3CCl_3 in troposphere, and CH_4 vertical profiles in the upper troposphere to mesosphere from limb-viewing satellite measurements.

The MIROC4-ACTM simulations of atmospheric CH4 have made for the period of 1984-2017 using the initial emissions from bottom-up inventories for anthropogenic sources (as in EDGARv432; Janssens-Maenhout et al., 2017), emissions from wetlands and rice paddies simulated by a terrestrial biogeochemical model (VISIT), forest fires from GFEDv4.1s remote sensing-based product, and the rest from TransCom-CH_4 experiment (Patra et al., 2011). An ensemble of 7 total CH_4 emissions are made for simulating CH_4. Global net CH_4 emissions varied between 530–545 and 545–610 Tg yr^{-1} in 1984–2004 and 2005–2017, respectively (ranges based on 7 inversion cases), with a step like increase in 2007. The inversion system did not account for interannual variations in OH radicals reacting with CH_4 in the atmosphere, but the sensitivity to the interhemispheric OH ratio is checked (Patra et al., 2014). The MIROC4-ACTM meteorology is nudged to Japanese 55-year Reanalysis (JRA55) of U, V and T, provided by JMA (Kobayashi et al., 2015).

Atmospheric CH_4 growth rates varied greatly, at about 15 ppb/yr increase during 1988-1991, 0-5 ppb/yr during 1992-2005, and 8 ppb/yr during 2006-2016. A reduction in wetland CH_4 emissions of about 20 Tg during 1991-1992, following the Mount Pinatubo eruption in June 1991, triggered the flattening of CH_4 growth rate in the early 1990s. The quasi-equilibrium in CH_4 during 2000-2006 cannot be simulated well by MIROC4-ACTM using a priori emission estimates, presumably due to the overestimated CH_4 emission from China's anthropogenic activities (Saeki and Patra, 2017). A global box-model calculation using the model-observation differences suggests an a priori emission underestimation by about 30 Tg/yr during 1984-2002. Further detailed CH_4 emissions from 53 land regions for the study period are being calculated using the global inverse modeling system (Patra et al., 2016).

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Poster session

P6 The Evolving role of Space Based Measurements in a Global Carbon Monitoring System

David Crisp

Early flux inversion studies indicated that space-based observations of X_{CO2} with accuracies of 1 ppm on regional scales at monthly intervals could substantially improve our understanding of CO_2 sources and sinks. Recent products from the OCO-2 mission are meeting or exceeding this target. In spite of this progress, and that anticipated from the growing fleet of greenhouse gas missions, improvements in measurement accuracy, precision, resolution and coverage are still needed to deliver timely information about CO_2 sources and sinks on the scale of individual nations or to track subtle trends in the natural carbon cycle resulting from climate change. Spatially- and temporally-correlated X_{CO2} biases must be reduced to vanishingly-small values (<< 1 ppm) to enable accurate local to regional scale CO_2 flux inversions. Greater single-sounding precision is needed to quantify trends in emissions from localized sources such as mega cities and power plants. Higher spatial and temporal resolution is needed to isolate discrete sources and sinks and to track their variations over diurnal to seasonal time scales. Improved coverage is needed, especially at high northern latitudes of the winter hemisphere and in tropical regions covered by persistent, optically-thick clouds. Some of these needs will require improved space-based instruments, calibration techniques, X_{CO2} retrieval algorithms, validation capabilities and flux inversion strategies. Others must be addressed by carefully coordinating the available space-based, aircraft, and ground-based sensors to produce a more effective greenhouse gas monitoring system. This presentation will summarize the progress and plans in these areas.

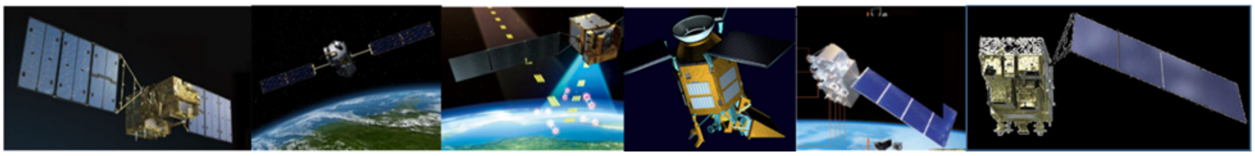

Figure 1: Currently operating GHG satellites: GOSAT, OCO-2, TanSat, Sentinel-5p, FengYun 3D, and Gaofen-5.

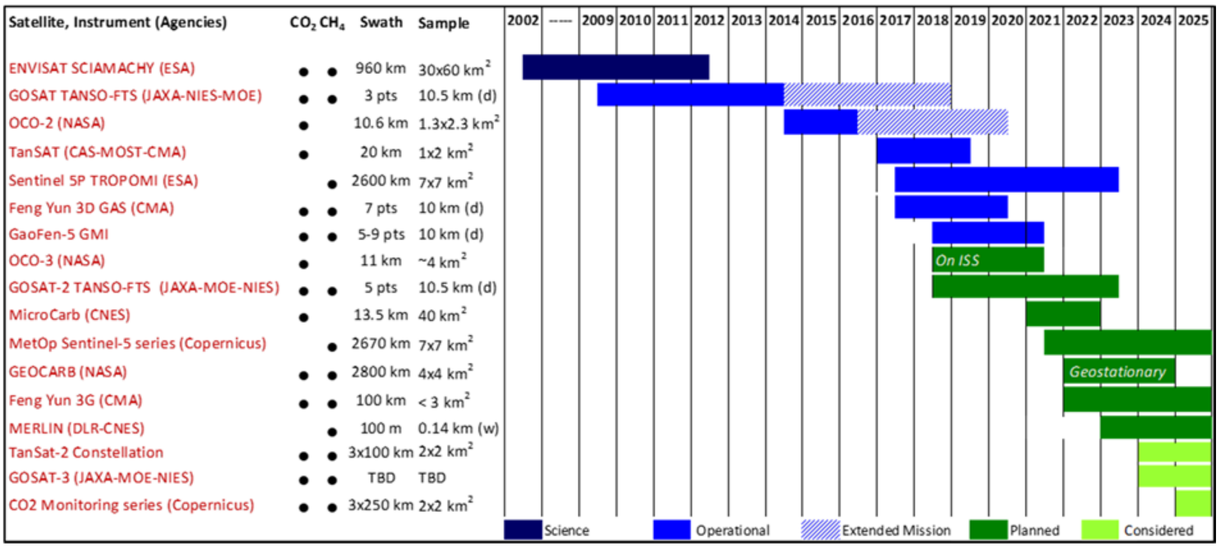

Figure 2: Past, present, and planned GHG satellites.

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Poster session

P7 Analysis of Fluxes and Uncertainties in the OCO-2 Level 4 Flux Product

Sean Crowell, Andrew Schuh, David Baker, Sourish Basu, Andy Jacobson, Junjie Liu, Liang Feng, Feng Deng, Dylan Jones, Paul Palmer

The OCO-2 Level 4 Flux Product represents an ensemble of top-down flux estimates from a wide range of transport models, prior flux estimates, prior flux uncertainties, and data assimilation methodologies. Important signals seen in the tropics point towards a more dynamic carbon cycle than previously expected from flux estimates as constrained by the global in situ network, though satellite driven top down estimates are well-known to be especially sensitive to bias as well as large scale transport errors. In this presentation, we explore the Product to diagnose the significance of these results and their sensitivity to these uncertainties.

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Poster session

P8 How much can atmospheric data tell us about the North American land sink?

Sha Feng, Thomas Lauvaux, Brian Gaudet, Arkayan Samaddar, Sandip Pal, Martha Butler, Klaus Keller, Kenneth J. Davis, Tomohiro Oda, Andrew Schuh, Andy Jacobson, David F. Baker, Sourish Basu, Junjie Liu, Kevin R. Gurney

Disaggregating the well-constrained global carbon budget into regional fluxes remains difficult. Continental CO2 fluxes are not well characterized due to the limited atmospheric data, uncertain atmospheric transport, and uncertain prior fluxes. The Atmospheric Carbon and Transport-America (ACT-America) mission aims to improve our understanding of transport and fluxes of greenhouse gases (GHGs) via aircraft campaigns that cover three regions of the U.S., four seasons, and a variety of synoptic weather conditions. Flight campaigns started in the summer of 2016 and have now been conducted in all four seasons, providing unique observations for evaluation of global and regional, forward and inverse GHG modeling simulation. We have assembled a suite of models to complement these observations. This suite includes the posterior predictions from global GHG inversion systems, a calibrated, continental-scale, 27-km resolution model ensemble including sub-ensembles of atmospheric transport, biospheric and fossil fuel fluxes, and boundary inflows, and a cloud-resolving (3 km resolution) regional simulation. We present the results from this multi-scale, multi-model, model-data evaluation effort.

The ensemble system can separate and quantify the uncertainty in the modeled CO2 from atmospheric transport, biospheric fluxes, fossil fuel emissions, and boundary inflows. The results suggest the role that each source of uncertainty plays in inverse flux estimates. Boundary conditions and fossil fuel emissions are larger contributors to the model uncertainty than expected, especially at longer time scales. Atmospheric transport is a large uncertainty source at shorter time scales, but its contribution appears to decay beyond synoptic scale. Boundary inflows play an important role in the large-scale modeled CO2 gradients. Evaluation of the ensemble system with ACT observations is underway. ACT-America data also have been used to evaluate the global inversions participating in the OCO-2 model inter-comparison project, helping us to understand the impact of assimilating column-averaged versus in-situ CO2 data on the posterior fluxes and to explore the transport uncertainty in the global inversions. Profiles from the summer 2016 campaign show a strong regional dependence of the model biases; many of the TM5 transport inversions show strong negative CO2 biases in the Mid-Atlantic below 4 km when only in situ data are assimilated; the use of column data greatly improves the biases. By contrast, in the Midwest most inversions tend to underestimate the vertical gradient of CO2 (lower concentrations near the surface) regardless of transport model or inversion method. The cloud-resolving simulation helps us understand the mechanism and main drivers of the carbon transport observed. The results from frontal cases in the ACT-America summer campaign demonstrate the CO2 gradients in stormy weather are mainly driven by horizontal advection and large-scale boundary inflows.

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Poster session

P9 CoMet: An airborne mission to simultaneously measure CO2 and CH4 using lidar, passive remote sensing and in-situ techniques

*Andreas Fix, and the CoMet team**

In order to improve our current knowledge on the budgets of the two most important anthropogenic greenhouse gases, CO2 and CH4, a co-ordinated measurement campaign in the Central European region will be carried out with the German research aircraft HALO and two smaller Cessna aircraft being its main experimental platforms. The goal of CoMet is to combine a suite of the best currently available airborne active (lidar) and passive remote sensors (spectrometer) with in-situ instruments to provide regional-scale data about greenhouse gases (GHGs) which are urgently required for their accurate modelling.

For CoMet, an intensive measurement period of 4 weeks is planned at the beginning of the growing season in May/June 2018 in Central Europe. During this period, optimized HALO research flights will comprise extended latitudinal transects to capture the GHG gradients, flights over known regions of strong emissions as well as comparison overflights over the ground-based remote sensing sites of the Total Carbon Column Observing Network (TCCON). While HALO will provide a larger scale picture, the two Cessna aircraft will concentrate on a region of prime interest: the Upper Silesian Coal Basin (USCB) in Poland. In this area which, due to hard coal mining activities, is known to be one of the European hot spots of anthropogenic methane emissions, a variety of additional ground-based instruments will support the CoMet mission: an array of several ground-bases FTIR instruments will be deployed here. Several wind lidars will accurately measure the local wind conditions to help inferring fluxes by means of e.g. mass balance approaches. In addition, in-situ measurements from mobile vans and small drones will be available through an in-kind contribution of the MEMO2 network to provide near-surface information of GHGs and to quantify CH4 and CO2 emissions from individual coal mining shafts. GOSAT and Sentinel-5P products will be used and compared with the respective ground-based and airborne instruments.

In order to assess regional scale fluxes from model results, a model infrastructure (regional inverse modelling, chemistry-climate modelling with regional refinement) will be employed in order to use the data streams of the individual instruments for modelling the greenhouse gas fluxes. With many vertical profile and column measurements across Europe the data provide an ideal testbed also for evaluation of transport models used within the TRANSCOM community.

The CoMet mission is also part of the validation activities for existing passive remote sounding GHG satellites, OCO-2, GOSAT, and Sentinel 5-P and preparation of the first active CH4 satellite mission MERLIN. In addition it will investigate methodologies for the synergistic combination for greenhouse gas measurements using lidar and passive remote sensing.

This contribution will present preliminary findings from the CoMet mission and the exploitation of the observations.

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Poster session

P10 Preliminary result of carbontracker-Asia 2016

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The National Institute of Meteorological Sciences has operated the carbontracker-Asia (CT-A) which is originated from the National Oceanic and Atmospheric Administration. The CT-A is an global inveron model based on ensemble Kalman filter. Additionally, the TM5 transport model, which simulates CO2 mole fractions on the globe, is employed. The CT-A adopts two-nested grid centered on East Asia (3x2 grid on the globe and 1x1 grid on the Asia). In particular, the CT-A assimilates additional CO2 observations at the site of Ryori, Yonagunijima, and Minamitorisima from the world data centre for greenhouse gases for the first time. Furthermore, the assimilation module for CO2 aircraft observation was implanted in the CT-A. We use the aircraft observation data from the comprehensive obsrvation network for trace gases by airliner project. In this study, we introduce the CT-A 2016 which was newly updated in 2017. Then the retrieved data for the period 2000~2015 are presented. In addition, in order to evaluate the impact of the observation data assimulation, we provide data as follows: (1) Difference before and after the aircraft data assimilation and (2) Difference in results on whether three observations in Japan are assimilated. After three sites CO2 data assimulation, significant uncertainty reduction was found.

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Poster session

P11 ICOS Carbon Portal: Elaborated products and services to support European carbon budget estimates

Ute Karstens, Naomi Smith, Alex Vermeulen, André Bjärby, Oleg Mirzov, Lars Harrie, Ingrid van der Laan-Luijkx, Christoph Gerbig, Frank-Thomas Koch, Margareta Hellström, Marko Scholze, Grégoire Broquet, and the Carbon Portal Team

ICOS Carbon Portal is the data center of the ICOS Research Infrastructure and the 'one stop shop' for ICOS data products. Carbon Portal is in charge of archiving and disseminating all ICOS measurement data. In addition, various elaborated data products, i.e. outputs of modelling activities based on ICOS observations, are compiled and distributed by Carbon Portal. In order to facilitate the creation of such elaborated products by the research communities themselves, Carbon Portal provides access to a variety of datasets that can be used as prior and ancillary information in models as well as atmospheric measurement data, e.g. in form of the ObsPack CO2 product GLOBALVIEWplus, for which the Carbon Portal has collected and processed contributions from the European laboratories. Carbon Portal actively supports the EUROCOM project in a collaborative reanalysis of European CO2 fluxes over the period 2006-2015. EUROCOM involves modellers from several European research institutes contributing results from a variety of inversion systems. Carbon Portal provides a platform for the collaborative analysis of the inversion results and eventually also for their further dissemination. Interactive tools for visualization, comparison, and synthesis of data and elaborated products are hosted at the Carbon Portal website. A first test instance of a Virtual Research Environment, based on Jupyter Notebook, allows users to execute interactive statistical analyses and visualizations of modelling results, emission inventories, and ICOS data sets via a combination of pre-prepared and user-specific Python scripts. On-demand calculation of atmospheric measurement station footprints is another service offered by Carbon Portal. This tool combines natural greenhouse gas fluxes from biospheric models and anthropogenic emissions with the lagrangian transport model STILT, in order to illustrate the time evolution of the geographical origin of the greenhouse gas signal that is measurable at a specific location, providing information for the design and assessment of measurement strategies.

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Poster session

P12 Updates from the GEO Carbon and Greenhouse Gas Initiative

Jouni Heiskanen, Antonio Bombelli, André Obregón, Nobuko Saigusa, and the GEO-C Team

The budgets of carbon and other greenhouse gases (GHGs) are associated with uncertainties which complicates to evaluate the success of climate change mitigation strategies. Improvements in long-term, high quality observing systems within and across the atmospheric, oceanic, terrestrial and human domains are required to quantify GHG sources and sinks, to understand the climate system, and to assess the level of effort required in order to mitigate and adapt to climate change.

Current carbon observation efforts are a mix of regional and global activities in different, often isolated, contexts. The GEO Carbon and GHG Initiative (GEO-C) in the framework of the Group on Earth Observations (GEO) promotes interoperability and integration across different efforts, particularly at domain interfaces. The aim is a comprehensive carbon and GHG observation and analysis system that provides data for scientists as well as useful and comparable information for resource managers and policy makers.

GEO-C builds on existing initiatives and networks, supports their continuity and coherence, and facilitates actions to fill in the missing pieces for an integrated global system. The initiative addresses policy agendas and operates as a common and open forum to plan and implement strategies and joint activities at the global level from science to policy. Currently GEO-C is working with key organisations such as UNFCCC, IPCC, WMO, GCOS, GCP, Copernicus, ICOS, CEOS, and IG3IS, to take stock of the contributions from all relevant actors, to identify existing gaps and to draft a common roadmap to reach the goals. This presentation will focus on the recent advancements.

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Poster session

P13 New computational approaches for high-dimensional GHG inversions and their applicability to a future CO_2 Human Emission (CHE) monitoring system for the European Union.

N. Bousserez, A. Agusti-Panareda, J. McNorton, R. Engelen, G. Balsamo, M. Choulga

Large-scale atmospheric source inversions, for which the size of the parameter and observation spaces precludes the computation of analytical solutions, rely on either ensemble-based (e.g., EnKF) or adjoint methods (e.g., 4D-Var). While ensemble-based approaches provide approximations of posterior error covariances along with the maximum a posteriori (MAP) solution, they are limited by the sampling noise associated with the inherent small size of the ensembles used. Standard variational approaches, on the other hand, are immune to sampling noise at the expense of computing many gradient calculations to minimize a cost function. Each gradient calculation requires a sequential integration of a forward or tangent-linear model followed by its adjoint counterpart, making 4D-Var minimizations computationally expensive. We introduce new techniques that blend the parallelism afforded by ensemble approaches with the efficiency of adjoint-based methods to capture the information content of the observational system. We demonstrate that the new method can reduce the walltime of the optimization by more than an order of magnitude compared to standard minimization approach, while providing key information content diagnostics, such as posterior error covariances and model resolution matrix approximations. We discuss the applicability of those algorithms in the context of the Carbon Human Emission (CHE) project, a new European Union initiative to build a prototype system for global anthropogenic CO2 emission monitoring

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Poster session

P14 The potential of space-based CO_2 retrievals to evaluate land surface models

Hannakaisa Lindqvist, Christopher O'Dell, Andrew Schuh

Space-based retrievals of column-averaged carbon dioxide (XCO2) help constrain the regional sources and sinks of atmospheric CO2 through data assimilation. However, this approach is sensitive to multiple factors, including residual regional-scale biases in the observations that may induce errors in the fluxes, and also potential error sources within the model inversion system (e.g., in the transport model, inversion setup, or prior flux components). We are investigating the benefits of a parallel research effort: we compare satellite-retrieved XCO2 directly to simulated XCO2 fields from models that assimilate in-situ measurements of CO2. We concentrate especially on quantitative comparisons of the regional XCO2 seasonal cycles from the Greenhouse Gases Observing Satellite (GOSAT) and the Orbiting Carbon Observatory -2 (OCO-2) to those from a variety of models.

We find that the XCO2 seasonal cycle amplitude from GOSAT and OCO-2 observations generally agrees with models 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. We explore the underlying reasons for these discrepancies by comparing model fluxes in these regions, and discover a systematic connection between a too shallow XCO2 seasonal cycle amplitude and a low variability in the net ecosystem exchange at the biome types of subtropical savannas, grasslands and seasonally dry forests. In these particular regions, the in-situ measurements of CO2 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. Our tests with different land surface models imply that models driven by NDVI of fPAR consistently underestimate the seasonality of the biospheric CO2 fluxes in these biomes, whereas models with prognostic plant growth lead to a better agreement with the GOSAT and OCO-2 satellites. The results of this study provide example guidance to what extent satellite-retrieved XCO2 can directly be used to learn about land surface models.

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Poster session

P15 CO2 flux inversions in the Washington DC / Baltimore metropolitan area: FLAGG-MD 2016 flight campaign

Israel Lopez-Coto, Xinrong Ren, Russell Dickerson, Paul Shepson, Olivia Salmon, Ariel Stein, Anna Karion, Kuldeep Prasad, James Whetstone

In February 2016, during the FLAGG-MD 2016 campaign, two airborne platforms were used to quantify GHG emissions from the Washington DC / Baltimore area, the Purdue University Beechcraft Duchess, housing the Airborne Laboratory for Atmospheric Research (ALAR), and the University of Maryland's Cessna 402B research aircraft. Both planes flew simultaneously for 5 days, mostly during the afternoon hours, collecting CO2 mixing ratio and meteorological data. Urban CO2 emission rates from the area are estimated from data collected by both aircrafts with a Bayesian inversion framework.

The dispersion model used in this work was the HYbrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT) for computing observation sensitivities, or footprints, to surface fluxes. To estimate the model-data mismatch error covariances, an ensemble of meteorological conditions derived from various atmospheric transport models were used to drive HYSPLIT. Five different meteorological products were used: the High Resolution Rapid Refresh (HRRR) NOAA operational forecast product and 4 configurations of the Weather Research and Forecasting (WRF) model. Four Planetary Boundary Layer (PBL) parameterizations (MYNN, YSU, QNSE and Boulac) were used in WRF along with 2 sources of initial and boundary conditions (NARR and HRRR) to drive it. One configuration also included the building energy parameterization (BEP) urban canopy model. The ensemble of transport models along with the wind speed and direction errors provides the means to estimate the model-data mismatch error covariances.

Nine CO2 anthropogenic emissions inventories were used in the inversion to test the sensitivity of the model predictions to the prior assumptions. Four of them (Vulcan, ODIAC, FFDAS and ACES) are publicly available inventories but for a different year. One inventory (DARTE) is a partial inventory and provided only transportation emissions. Another is the mean of the previous five (Ensemble), and the rest (Flat and Simple) are constructed here for sensitivity testing purposes. The flat prior assumes that the entire domain emits with a single uniform emission value while the simple prior is constructed by assigning an emission value per pixel based upon that pixel's urban fraction, the road locations and the point source emissions, taken from the EPA GHGRP.

Inversion results were consistent between days across inventories and transport models. As expected, the flat prior showed the larger variability in the results due to the loose initial constraint that it imposes on the inversion. The inclusion of the non-diagonal elements in the model-data mismatch error covariances impacted the results on a case by case basis. In addition, the inversion results reflected the fact that February CO2 emissions are typically larger than the annual mean for the area.

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Poster session

P16 Estimating UK emissions of greenhouse gases from observations and comparison with national inventories

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Verification of the UK Greenhouse Gas Inventory (GHGI) is considered to be best practice by the United Nations Framework Convention on Climate Change (UNFCCC) as it allows for an independent assessment of the GHG emissions from a country using a comprehensively different approach to the inventory. Significant differences in the emissions estimated using the two methods are a means of identifying areas worthy of further investigation, for example as occurred with a re-assessment of the emissions of HFC-134a from mobile air conditioning in the UK.

In order to provide verification of the UK GHGI, BEIS (UK Department for Business, Energy, and Industrial Strategy) fund the University of Bristol (UoB) to maintain a high-quality atmospheric observation station at Mace Head (MHD) on the west coast of Ireland. The station reports continuous, high-frequency concentrations of the key greenhouse gases. In 2012 BEIS funded the UoB to extend the measurement programme with three new tall tower stations across the UK (UK DECC (Deriving Emissions linked to Climate Change) network): Tacolneston (TAC) near Norwich; Ridge Hill (RGL) near Hereford; Tall Tower Angus (TTA) near Dundee, Scotland (relocated to Bilsdale (BSD) in North Yorkshire in Sept 2015). Methane, carbon dioxide, nitrous oxide and sulphur hexafluoride (SF6) are measured across the UK DECC network, with all of the other reported gases only measured at MHD and TAC.

A Lagrangian dispersion model NAME (Numerical Atmospheric dispersion Modelling Environment), driven by three-dimensional modelled meteorology, is used to interpret the observations. NAME determines the history of the air arriving at the time of each observation. By estimating the underlying baseline trends (Northern Hemisphere mid-latitude atmospheric concentrations where the short-term impact of regional pollution has been removed from the data) and by modelling where the air has passed over on route to the observation stations on a regional scale, estimates of UK emissions are made. A methodology called Inversion Technique for Emission Modelling (InTEM) has been developed that uses a minimisation technique, Non-Negative Least Squares, to determine the emission map that most accurately reproduces the observations. The results of the comparison between the GHGI and the InTEM estimates will be presented and how the UK government uses the comparative information to guide their national GHGI improvement programme.

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Poster session

P17 Overview of the CO2 Human Emissions (CHE) Project

Joe McNorton, Nicolas Bousserez, Anna Agusti-Panareda, Gianpaolo Balsamo, Richard Engelen

The CHE project consortium, which consists of 22 European partners, aims to coordinate efforts towards the development of a European system to monitor anthropogenic CO2 emissions. Well-informed policy decision making for CO2 emission reductions requires detailed attribution of anthropogenic emissions by country and by region, which itself requires an effective monitoring system.

The CHE project aims to deliver a proof of concept system which, given a potential future Earth observation system based on a constellation of satellites and a ground-based observing network, can provide a representation of anthropogenic emissions at a required spatial and temporal scale to inform policy. This will require methodological development in integrating the components of a proposed Earth observation monitoring network with bottom-up and top-down constraints, which includes a focus on observational and model uncertainties. Additional information from isotopes and other co-emitted tracers, as well as biogenic flux estimates will be explored to support anthropogenic CO2 source attribution and uncertainty reduction. Here we provide an overview of the project and present work currently in development.

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Poster session

P18 Regional CO_2 inversions with LUMIA, the Lund University Inversion Algorithm

Guillaume Monteil, Ute Karstens, Marko Scholze

Within the framework of the EUROCOM project, we developed LUMIA, the Lund University Modular Inversion Algorithm. LUMIA is an atmospheric inversion model, that is the coupling of an atmospheric transport model (currently FLEXPART-based) and of a variational minimization algorithm. Within EUROCOM, LUMIA was originally designed to compute regional (European) estimates of NEE at a half degree resolution, based on surface CO_2 observations from the ICOS network. LUMIA was however developed with the overarching objective of being adaptable to a wider range of problems (different scales, tracers and observation types), and in particular, one of the long term goals is a form of coupling with the LPJ-GUESS model developed also at Lund University.

That adaptability objective is achieved through a modular design of the inversion setup. In particular, the inversion algorithm is independent from the transport model, which makes transport models easily exchangeable. In its current setup, LUMIA computes tracer transport using pre-computed observation footprints from Lagrangian transport models (FLEXPART, STILT), with background concentrations derived from coarse resolution TM5-4DVAR inversions. This allows not only for faster inversions (the transport does not need to be recomputed at each iteration, and the whole system is easily parallelizable), but also a better adaptability of the transport model to the resolution of the bottom-up fluxes, as observation footprints can be computed on arbitrary grids, matching those of the prior.

LUMIA is already used to produce European CO_2 inversions for the EUROCOM project, using prior NEE fluxes from LPJ-GUESS. Here we will present some of these results, but we will focus on results from additional inversion experiments, mainly on the validation of the model (synthetic inversions, sensitivity and performance assessments). We will also discuss the future developments of the model, and its availability to the community.

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Poster session

P19 Updates of CO2 inversion analysis at Japan Meteorological Agency

Takashi Nakamura, Takashi Maki

For monitoring of GHGs under the framework of WMO/GAW programme, the Japan Meteorological Agency (JMA) maintains multiple platforms of GHG observation, operates one of the WMO/GAW data centres (World Data Centre for Greenhouse Gases; WDCGG), and performs 30-year analysis of global CO2 concentration distribution from 1985 with an inversion method.

This 30-year analysis, called JMA CO2 distribution, is obtained by Bayesian Synthesis Inversion method using a numerical tracer transport model with non-fitted (screening process only) observation data (Maki et al., 2010). Since the release of first analysis in 2009, the results have been updated annually as global distribution maps of monthly mean CO2 concentration on JMA's website. In 2017, the analyzed CO2 concentrations data were also made available as grid point values (GPV) on the JMA website (https://www.data.jma.go.jp/ghg/kanshi/co2data/co2_mapdata_e.html). Currently, version 2018, covering from 1985 to 2016, is available.

For better analysis (reduce uncertainty and discrepancy from actual data), JMA has been improving our transport model, emission assumption, and usage of observation data. In 2016, JMA introduced a new tracer transport model (GSAM-TM), instead of the previous tracer transport model (CDTM; Sasaki et al., 2003), and started to use monthly maps of historical fossil fuel consumption (Andres et al., 2013) and JMA's oceanic CO2 exchange (Iida et al., 2015).

For further improvement of JMA's CO2 analysis, JMA continues developing its tracer transport model, enhancing use of background emission and observation data, and upgrading inversion analysis.

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Poster session

P20 Origin of methane growth rate anomalies from the atmospheric transport

Sudhanshu Pandey, Sander Houweling, Ilse Aben, Thomas Röckmann, Narcisa Banda, Maarten Krol

The atmospheric burden of CH4 is determined by the net effect of its sources and sinks. It is calculated by extrapolating the CH4 mixing ratio measurements, made by global measurement networks like NOAA, CSIRO in space and time. We show that the atmospheric transport, in combination with a limited sampling density of atmospheric measurement networks, can give rise to growth rate anomalies which are not due to any source or sink changes. This means that any concentration-to-flux conversion method not accounting for the atmospheric transport will erroneously assign the transport/sampling-related anomalies to source/sink changes.

We quantify the transport/sampling-related biases in CH4 growth rate using surface and satellite measurements and atmospheric transport model run with annually repeating sources and sinks of CH4. We show that during extreme events, such as the 1998 El Niño and 2011 La Niña, the transport anomalies became significant for determining budgets for hemispheric up to global scales, and seasonal up to annual scales. We find that the transport biases become less significant on longer (half-decadal) time scales as the atmosphere gets well mixed.

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Poster session

P21 A global 3D model for the triple oxygen isotopic ratios ^{17}O in atmospheric CO_2

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Keywords: atmosphere, gross primary production (GPP), 3D transport model, stable oxygen isotopes, mass-independent fraction (MIF)

The gross uptake of CO_2 by vegetation through photosynthesis, widely known as gross primary production (GPP), is a key process in the carbon cycle that strongly affects the atmospheric CO_2 abundance, yet its magnitude is currently poorly constrained. The triple oxygen isotopic ratios of atmospheric CO_2, denoted by $\Delta^{17}O$ (or ^{17}O-excess), was recently put forward as a potential tracer of GPP. In this study a global modeling framework has been developed for predicting the temporal variation and spatial distribution of $\Delta^{17}O$ in atmospheric CO_2 (defined as: $\Delta^{17}O = \ln(\delta^{17}O+1) - 0.5229 \cdot \ln(\delta^{18}O+1)$).

The $\Delta^{17}O$ signature of atmospheric CO_2 (~50 per meg near the surface) originates from photolysis of O_3 in the stratosphere where mass-independent fractionation of the stable oxygen isotopes ^{16}O, ^{17}O and ^{18}O occurs. This fractionation signal is transferred from O_3 to many other oxygen-containing gases, including CO_2 (+1500 per meg in the lower stratosphere). Following transport to the troposphere, the $\Delta^{17}O$ of this CO_2 is 'reset' (to nearly 0 per meg) by isotope exchange with liquid water, mostly in the leaves of vegetation where isotopic equilibration occurs with the more abundant H_2O. Due to the presence of the enzyme carbonic anhydrase (CA), the effectiveness of exchanging oxygen isotopes between CO_2 and H_2O in vegetation is high. The dominance of this biospheric loss term in determining the $\Delta^{17}O$ tropospheric abundance makes it a potential tracer for GPP.

Our 3D model for $\Delta^{17}O$ in CO_2 is based on the global atmospheric transport model TM5 driven by meteorological fields from the European Centre for Medium-Range Weather Forecasts (ECMWF) and uses CO_2 surface fluxes from the data assimilation system CarbonTracker. We model the stratospheric source of the $\Delta^{17}O$ signal in CO_2 by imposing the observed N_2O-$\Delta^{17}O$ correlation for stratospheric CO_2 on $\Delta^{17}O$ through our simulated N_2O mixing ratios, with a user-specified relaxation time constant. The vegetation sink of $\Delta^{17}O$ is modeled with the Simple Biosphere/Carnegie-Ames-Stanford Approach (SiBCASA) model, which allows for explicit calculation of gross CO_2 fluxes, based on internal and external CO_2 concentrations of leaf stomata for C_3 and C_4 vegetation types. Also, the effect of soil invasion fluxes, ocean exchange, fossil fuel combustion and biomass burning is incorporated into the $\Delta^{17}O$ model.

In addition to the resulting $\Delta^{17}O$ global and regional balances, we will present the magnitude and variability of the simulated tropospheric $\Delta^{17}O$ signal, and the amplitude and timing of its seasonal fluctuation compared with existing measurement series for $\Delta^{17}O$ in tropospheric CO_2. Parallel to this modeling study a measurement program for $\Delta^{17}O$ in CO_2 over the Amazon with small aircraft is performed. The ultimate goal of the

project is to combine our $\Delta^{17}O$ model with measurements over the Amazon to constrain the Amazonian GPP.

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Poster session

P22 Responses of atmospheric CO_2 seasonality to vegetation green-up advancement of deciduous forest in the Northern Hemisphere

Hoonyoung Park, Su-Jong Jeong

Vegetation growing season advances toward spring facing global warming. This advancement of vegetation activity strengthens terrestrial carbon uptake through biogeochemical processes and induces a change in atmospheric CO2 seasonality. However, the influence of spring green-up advancement on the CO2 seasonality is still unclear due to various natural and anthropogenic carbon sources. Here we used Community Earth System Model (CESM) to assess the responses of the CO2 seasonality to green-up advancement. We performed three full-coupled and prognostic-CO2 simulations with original and decreased spring onset thresholds (80% and 60% of the original threshold) of deciduous forests to make the green-up date earlier. By the threshold relaxation, the green-up date was severely advanced especially in Europe (7.5 and 17.7 days) and the eastern part of North America (8.2 and 18.1 days) in the two experiments. This advancement of spring green-up date enhanced net primary production of deciduous forests around the date of green-up. It resulted in longer carbon uptake period and earlier spring zero-crossing date of the CO2 seasonality in the Northern hemisphere. Details will be shown in the workshop.

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Poster session

P23 A comparison of top-down CO2 fluxes derived from satellites and surface measurements with bottom-up constraints

Penelope Pickers, Corinne Le Quéré, Sander Houweling, Wouter Peters

Global and regional CO_2 flux estimates have large uncertainties reflecting limits in understanding of carbon cycle processes and in socio‐economic statistics, which restricts our ability to predict carbon cycle behaviour under a changing climate. There is potential to reduce existing uncertainties by using additional information from atmospheric constraints. "Top-down" methods to quantify CO_2 fluxes utilise atmospheric measurements, either from satellites or from the surface measurement network, combined with atmospheric transport modelling. There is currently significant disagreement between top-down estimates, and "bottom-up" CO_2 flux estimates derived from accounting‐based inventories, process modelling and data-based products. Furthermore, top-down estimates from satellite measurements often differ significantly from top-down estimates using surface measurements. As part of the EU funded CHE (CO_2 Human Emissions) project (https://www.cheproject.eu/), we conduct a comparison of top-down and bottom-up land and ocean CO_2 flux estimates from the most recent Global Carbon Budget (Le Quéré *et al.*, 2018) with top-down estimates from a suite of satellite-based inversions. We examine differences in both total fluxes and interannual variability over a range of spatial scales. We seek to identify how similarities and discrepancies vary with spatial scales and time-frames. Correctly identifying discrepancies in CO_2 flux estimates over different spatial and temporal scales is an important step towards understanding the sources of the differences between top-down and bottom-up estimates, and how they can be resolved.

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Poster session

P24 Urban greenhouse gas emissions assessment: observations and modelling in a pilot study for the Oslo area

Ignacio Pisso, Susana Lopez-Aparicio, Philipp Schneider, Matthias Vogt, Franck, Norbert Schmidbauer, Terje Krognes.

Norway has set the target of cutting greenhouse gas (GHG) emissions by at least 40% compared to 1990 levels by 2030. This goal will require the implementation of policy measures aiming at strong reductions of GHGs emissions, especially in the urban environment. The implementation of urban policy measures is still a challenging task and it requires control and verification for success. The URGE project aims at assessing the GHGs emission flux methodologies including comprehensive uncertainty estimates based on inverse transport modelling techniques and optimized use of measurements, in order to establish a coherent and consistent GHG urban emission inventory. This is being be carried out in a case study in Oslo, where CO2 is be the priority compound. The overall outcome of the project is expected to provide support in the development of strategies to effectively reduce GHG emissions in the urban environment. The main activities are establishing the baseline urban CO2 emission inventory for Oslo; determining the optimal measurement locations based on transport modelling; designing and carrying out a pilot measurement campaign of the CO2-rich air downwind of the city plume combining state-of-the-art instruments and low cost sensors; assessing the feasibility of determining the background concentration surrounding the city (with e.g. satellite measurements); and providing optimised estimates of the emissions and their uncertainties via inverse modelling (source-receptor relationship based optimisation). We are interested the inter-operability and exchange of information with similar activities in other urban areas. We will present the overall project and the preliminary results, discuss the data exchange formats, the algorithms and data structures that could be used for inter-comparisons and the suitability to apply the techniques to other atmospheric compounds.

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Poster session

P25 Multi-scale greenhouse gas flux estimation systems in support of Canadian carbon cycle science and policy

Saroja Polavarapu, Douglas Chan, Felix Vogel, Vikram Khade, Jinwoong Kim, Michael Neish

Environment and Climate Change Canada has a multi-scale approach to the development of comprehensive carbon data assimilation systems. The desire is to obtain flux estimates of CO2 and CH4 over Canada from national to provincial to urban scales using atmospheric and geophysical observations from a variety of platforms (in situ and remote sensors). These systems are needed for addressing carbon science questions from the Canadian perspective such as: the quantification of natural sources and sinks of CO2 in boreal regions; the monitoring of GHG emissions over a potentially thawing permafrost; the capacity to detect the impact of potential mitigation efforts on CO2 and CH4 emissions; and supporting the efforts of ECCC's National Inventory Reporting group with independent information. The global scale system is called EC-CAS (ECCC Carbon Assimilation System) and the atmospheric transport and assimilation schemes are based on operational codes (the operational environmental forecast model and ensemble Kalman filter) from the Canadian Meteorological Centre. EC-CAS global GHG distributions (on a 90 km grid) are then used to constrain the regional (10 km grid size) model on the North American domain. The regional model concentrations can then provide background concentrations to the urban scale inversions. The urban scale project over the Greater Toronto and Hamilton area (led by F. Vogel) is part of the IG3IS test bed, which aims to provide actionable information on GHG emission (trends) to stakeholders at different governmental levels. This presentation will provide an overview of the ECCC plans and a discussion of the unique insights and challenges of modelling and assimilating GHG observations with a coupled meteorological and GHG transport model.

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Poster session

P26 CAMS CH4 flux inversions 1991-2016

Arjo Segers, Sander Houweling

Under the Copernicus Atmospheric Monitoring Service, a time series of global CH4 flux inversions from 1991 onwards is produced operationally with yearly extensions.

The product consists of monthly estimates of CH4 fluxes from four categories (wetlands, rice, biomass burning, and anthropogenic sources), at a resolution of 3x2 degrees globally. The production chain is based on a 4D-var inversion around the TM5 simulation model. A primary inversion stream analyzes surface observations from the NOAA network, and covers the period from 1991 onwards. A second inversion stream also analyzes GOSAT XCH4 observations from 2009 onwards, incorporating information from the NOAA-only stream for application of a bias correction.

The latest release completes the entire period 1991-2016 for the inversion using NOAA surface observations. Compared to the a priori emission inventories, the inversion product shows changes in the seasonal pattern of especially wetlands and anthropogenic sources. The product has been validated by comparing simulated CH4 concentrations with surface observations, XCH4 observations from the TCCON network, and aircraft observations from various campaigns.

The current release forms the base for yearly extensions using the latest available data, and will be regularly reprocessed after updates of the production chain.

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Poster session

P27 Exploring the global methane budget in a 3D model using statistical emulation

Angharad Stell, Dr Luke Western, Dr Matthew Rigby

Methane is the second most important greenhouse gas, but its budget is poorly understood: emissions inventories do not match the atmospheric observations. A lot of effort has been put into atmospheric modelling of global methane to try to reduce this discrepancy. Currently, three-dimensional global atmospheric models of methane have their emission and loss maps scaled manually in an attempt to match these to observations. The large parameter space and the uncertainty in the parameters means that there are many possible combinations which could explain the budget discrepancy. It is, however, computationally prohibitive to test all of these parameter combinations using a full atmospheric model. To make this task computationally feasible, this work emulates a global Chemistry transport model, MOZART, using a statistical model. This reduces the computational time of a single model run from hours to milliseconds and makes it possible to investigate all possible parameter combinations. An emulator allows a much more detailed underlying model to be used to infer global methane sources and sinks, whereas previous global work has largely focussed on box models. An additional benefit is that the method returns a probability distribution of the possible parameter space, rather than a single value of best fit. The result is a thorough understanding of which parameters it is most important to study to understand the global methane budget.

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Poster session

P28 Consistency in co-monitored CO_2 differences between iconic baseline sites offer further constraints on the global carbon budget

*Roger Francey, Rachel Law, Cathy Trudinger**

Co-monitoring by SIO, NOAA and CSIRO of baseline CO_2 spatial differences between Mauna Loa and Cape Grim or South Pole yields ensemble monthly averages in which uncertainties resulting from calibration propagation and inter-annual equatorial terrestrial air-surface exchange are suppressed. Between 1992 and 2017 the CO2 difference between hemispheres has increased primarily as a result of fossil fuel combustion in the Northern Hemisphere; the mean difference between hemispheres for these sites is 3.0 ppm with the mean of the monthly standard deviations being 0.23 ppm (as an indication of measurement precision, for Cape Grim minus South Pole the respective numbers are -0.10, 0.16 ppm). Understanding inter-hemispheric transport is important for interpreting this record; three month periods that correspond to eddy (Boreal winter) and advective (Boreal summer) inter-hemispheric exchange processes are examined and compared with transport model simulations.

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Poster session

P29 Evaluating carbon fluxes in sub-Saharan Africa during drought conditions using the coupled PCR-GLOBWB - SiB4 model

Erik van Schaik, Lars Killaars, Gerbrand Koren, Naomi Smith, Liesbeth Florentie, Ingrid van der Laan-Luikx, Wouter Peters

A major uncertainty in the contemporary global carbon budget is how the tropical biosphere is affected by droughts. Reductions in precipitation can alter the surface energy budget, decrease soil-moisture and river runoff, and change the land-atmosphere exchange of water and carbon over large areas. In this study we couple the advanced hydrological model PCR-GLOBWB to the terrestrial biosphere model SiB4 to investigate the large-scale response of (sub-)tropical vegetation during recent droughts in sub-Saharan Africa. We focus specifically on how evapotranspiration (ET), water-use efficiency, leaf area index (LAI) and carbon fluxes react to moisture deficits. We compare the results to satellite-derived products such as MODIS LAI, GLEAM ET, SIFTER sun-induced fluorescence and GRACE moisture anomalies to evaluate model performance and assess region-dependent responses of vegetation to drought conditions. The new model framework will later be used to evaluate spatiotemporal patterns of water-use efficiency and carbon fluxes over Amazonia as part of the ASICA project.

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Poster session

P30 Comparison of Korean carbon emission inventory with satellite-measured XCO2 from Orbiting Carbon Observatory-2

Jaeho Yeo & Su-Jong Jeong

Due to the uncertainties of the national greenhouse gas emission inventories, it is necessary to verify the national GHG emission inventories and comparison this with the using of atmospheric greenhouse gas observations for emission estimates. Recent studies suggested that satellite instrument can provide a detecting biases in reported emission inventories. In this study, we compared the estimates from satellite-based concentration measurements with the greenhouse gas inventories, by applying the preceding research's methods and analyzing column integrated XCO2 from Orbiting Carbon Observatory-2 (OCO2) and CO2 emission from GHG inventories in South Korea. Our results show some discrepancies between two data. More details in our study will be shown in the workshop.

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Poster session

P31 Contribution of terrestrial carbon budget to atmospheric CO2, in South Korea

Jeongmin Yun, Su-Jong Jeong, Chang-Hoi Ho

Atmospheric CO2 concentration has been steadily increasing since pre-industrial times due to anthropogenic CO2 emissions. A great uncertainty exists in the estimate of contribution of terrestrial carbon budgets to the increasing atmospheric CO2 at the national level. Here, we use tower observations of atmospheric CO2 concentration and a trajectory model to investigate temporally resolved CO2 fluxes in South Korea. From 19-year records at Anmyeondo, we estimate regional CO2 fluxes by comparing CO2 concentration values (ΔCO2) when wind comes from land sectors or ocean sectors. We verify that the CO2 data at ocean and land sectors act as a background and regional value from analysis of back-trajectories derived from Hybrid Single-Particle Lagrangian Integrated Trajectory model, respectively; 87.8% of ocean sectors' air parcels enter the observation site from ocean side and 79.1% of the land sectors' air parcels enter the observation site from land side, suggesting regional CO2 fluxes are well separated. We find that climatological annual and growing season (May through October) mean of ΔCO2 is 0.86 ppm and -1.78 ppm. More detailed results will be shown in the workshop.

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Poster session

P32 Satellite bias estimation system by independent CO2 inversion analysis

Takashi Maki, Takashi Nakamura

In recent years, many greenhouse gas observation satellites have been launched and operated. The satellite observation has advantages such as its wide observable area and spatial representation close to the model horizontal resolution. On the other hand, satellite observation has a critical issue of bias. This bias varies spatiotemporally. We need to properly evaluate and correct this bias if we try to use satellite observation data in carbon cycle analysis. Many researchers have attempted to verify the bias of satellite observation data by direct observations. However, the number of ground observation sites are limited and it is insufficient to evaluate the bias of satellite observation with a vast observable area in detail. We tried a method to evaluate bias of satellite observation data with independent inverse analysis data (JMA CO2 distributions). The analysis contains 30 years (1985-2016) CO2 monthly concentrations and we have calculated XCO2 from the analysis. We have calculated average bias data of satellite observation data by averaging differences from monthly satellite observation data and independent analysis values in order to extract signal and remove noise. The global average bias of GOSAT observation data (NIES L2 Ver. 2.X) throughout the whole period (2009-2016) was -1.2 ppm, almost consistent with verification results by ground observations. Looking at the geographical distribution, the bias of the GOSAT observation data showed relatively large seasonal change at the land area. By using satellite observation data after this bias correction method using the inverse analysis, we can expect to obtain CO2 flux analysis results consistent with conventional inverse analysis.

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Poster session

P33 Accelerating rates of Arctic carbon cycling revealed by long-term atmospheric CO_2 measurements

Su-Jong Jeong, A. Anthony Bloom, David Schimel, Colm Sweeney, Nicholas C. Parazoo, David Medvigy, Gabriela Schaepman-Strub, Chunmiao Zheng, Christopher R. Schwalm, Deborah N. Huntzinger, Anna M. Michalak, Charles E. Miller

The contemporary Arctic carbon balance is uncertain and the potential for a permafrost carbon feedback of anywhere from 50 - 200 PgC compromises accurate 21st century global climate system projections. The 42-year record of atmospheric CO2 measurements at Barrow, Alaska (71.29 N, 156.79 W) reveals significant trends in regional land-surface CO2 anomalies (ΔCO2), indicating long-term changes in seasonal carbon uptake and respiration. Using a carbon balance model constrained by ΔCO2, we find a 13.4 % decrease in mean carbon residence time (50% confidence range = 9.2 - 17.6%) in North Slope tundra ecosystems during the past four decades, suggesting a transition towards a boreal carbon cycling regime. Temperature dependencies of respiration and carbon uptake suggest increases in cold season Arctic labile carbon release will likely continue to exceed increases in net growing season carbon uptake under continued warming trends.

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Poster session

P34 KMA's Pilot Project Plan for WMO IG3IS

Yuwon KIM, Seoungwoon NOH, Su-ki LEE

As international agreements on GHG emission are legally binding, it is necessary to provide objective and quantitative information on absorption and emission of greenhouse gases. To guide greenhouse gas emission-reduction actions on the basis of sound scientific evidence, WMO has implemented the Integrated Global Greenhouse Gas Information System (IG3IS) as a global coordination mechanism. Especially, East Asia, where there are several major emitters of GHG as China, Japan and Korea, needs to establish a system to diagnose GHG fluxes accurately and reduce their uncertainty. Also, Ecological distinctiveness and uncertainty in the NIR of East Asia have become major obstacles to estimate GHG emissions from the ground. Therefore, KMA's implementation of IG3IS at the national level is meaningful in that it enables estimating realistic GHG emissions in East Asia. In order to implement national IG3IS, KMA is trying to develop a detailed implementation plan with scientific advisory group after understanding the status of domestic existing research. In the 1st phase, 2018~2020, KMA will invest to develop major technologies such as inverse methodologies with the help of NIMS (National Institute of Meteorological Science) and academia (for three years). In addition, KMA will continuously communicate with consumers, including inventory agencies, to ensure that the results of the project are in line with the direction desired by the consumers. Finally, KMA plans to evaluate the effectiveness in Phase I projects and to advance the technology in Phase II projects. KMA expect WMO and many countries to help the KMA's national IG3IS project proceed well, so it could contribute to implement the international programme.

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Poster session

P 35 Fast-response inversion of volcanic and nuclear source terms inside the EUNADICS

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Aviation shows vulnerability with regard to "airborne" hazards, including volcanic ash and sulfur clouds, nuclear accidents and other high-density aerosol plumes such as sand storms and forest fires. While several observation networks and satellites provide large amount of data that are relevant for the monitoring of such events, their integration to provide a timely best possible analysis of these hazards is one of the objective that the EU/H2020-funded EUNADICS-AV project is tackling.

A multi-model system, based on MATCH (from SMHI), MOCAGE (from Meteo-France) SILAM (from FMI) and WRF-Chem/Flexpart (from ZAMG) is being developed in EUNADICS-AV. Each model assimilates measurements relevant to the hazards: aerosols and SO2, from ground-based networks (lidars), satellites (AOD, ash retrievals, SO2 columns) and in-situ measurements (radionuclides). Ensemble or variational approaches are developed to estimate the point-source emission terms. The integration of the distributed observational information provide a harmonized 4-D (space- and time-resolving) quantitative analysis of the crisis situation.

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Poster session

P36 A joint regional carbon-atmosphere inversion system with explicit treatment of transport uncertainties

Hans Chen

Atmospheric inversions typically solve for surface CO2 fluxes using observed atmospheric CO2 mole fractions in a Bayesian framework, and use an atmospheric transport model as the forward operator to relate fluxes to atmospheric CO2. In this framework, however, it is not trivial how to represent atmospheric transport uncertainties due to systematic model errors and errors in meteorological initial and boundary conditions. Here we present a new regional inversion system based on advanced data assimilation techniques that solve for CO2 fluxes in a sequential time-stepping procedure. The data assimilation system is based on the ensemble Kalman Filter (EnKF) and uses the Weather Research and Forecasting model coupled with Chemistry (WRF-Chem) as the atmospheric transport model. By coupling the carbon and atmospheric states, we show that the EnKF can optimize CO2 fluxes while explicitly accounting for flow-dependent atmospheric transport uncertainties through an ensemble of perturbed transport forecasts. Furthermore, this approach scales well with increasing number of observations from e.g. high-density satellite measurements, and can solve for CO2 fluxes at the native model resolution. We present a series of perfect model experiments to test the EnKF inversion system, and introduce some data assimilation techniques to deal with spatial heterogeneity and filter divergence.

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Poster session

P37 Zooming into Cities: How can we Determine Greenhouse Gas Emissions at Sub-urban scales?

John C. Lin, Logan Mitchell, Ben fasoli, Lewis Kunik, Derek Mallia, Christopher Loughner, Zriel Stein, Ryan bares, Daniel Mendozq, Steven C. Wofsy, James Ehleringer

Urban areas are responsible for a significant proportion of the world's anthropogenic carbon emissions. As the global population increasingly moves to cities, the role of urban emissions in determining the future trajectory of carbon emissions is magnified. Evaluating these urban carbon emissions presents challenges in accounting for the extreme heterogeneity in land use and human activity while considerable opportunities also exist to make use of the diverse data streams and infrastructure available in cities. When these assets are combined with advances in instrumentation, inventory development, modeling/computing, and inverse analyses, progress can be made on quantifying and understanding sub-urban scale carbon emissions within cities.

We report new modeling and observational approaches to understand carbon emissions from the Salt Lake City metropolitan region, which is the locus for several critical assets: (1) one of the longest running urban CO_2 networks in the world; (2) light-rail based, automated greenhouse gas measurement system for measuring intra-urban gradients in CO_2 and other trace species; (3) an extensive meteorological measurement network that help to interpret the atmospheric observations and test the models.

The aforementioned data are integrated in an atmospheric modeling and inverse analysis system to estimate urban carbon emissions from the city. The modeling system includes high-resolution atmospheric models along with representations of emissions from traffic, buildings, and the biosphere.

Finally, we discuss this work in the context of a new effort in the U.S. entitled the *CO_2-Urban Synthesis and Analysis network* ("CO_2-USA"). The CO_2-USA network, working in collaboration with IG3IS, seeks to link U.S. cities to exchange information on community standards and common measurements, facilitate data sharing, and create analysis frameworks and cross-city syntheses to catalyze a new generation of researchers and enable new collaborations tackling important objectives that are difficult to address in isolation. We will especially report on the development of a harmonized urban greenhouse dataset and a cross-city atmospheric modeling/inverse system.

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Poster session

P38 Tropical Biomass Burning Observed By CO Inversions Assimilating MOPITT And Surface Observations

Hélène Peiro and Sean Crowell

Carbon monoxide (CO) is an important atmospheric trace gas for air quality studies. Atmospheric inversion of CO concentration is used to quantify the transport and the sources of CO in the troposphere. Despite the great accuracy in the lower troposphere of the surface observations, their limited coverage over the globe decrease our ability to understand the spatiotemporal distribution of CO sources, unlike the satellite instruments such as the Measurements of Pollution in the Troposphere (MOPITT) onboard the NASA Terra satellite.

The purpose of this poster is to assess the information in MOPITT observations related to biomass burning over the tropics during the year 2015.

A 4D-VAR data assimilation system has been used in the chemistry transport model TM5 to assimilate MOPITT data and surface observations from the ESRL GMD (Earth System Research Laboratory Global Monitoring Division) of the NOAA (National Oceanic and Atmospheric Administration). We used the 6x4 global version of TM5 with 25 vertical sigma hybrid levels.

In order to evaluate the impact of MOPITT data, CO inversions assimilating surface observations are first computed and then we jointly assimilated the MOPITT data with the surface observations. CO profiles from aircraft observations and total columns from Total Carbon Column Observing Network (TCCON) serve as validation data. We assess the improvement of using MOPITT and surface observations to study the CO production in the biomass burning which is in agreement with the aircraft and TCCON data.

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