THE GREENHOUSE GAS PROJECT OF ESA'S CLIMATE CHANGE INITIATIVE (GHG-CCI): OVERVIEW, ACHIEVEMENTS AND FUTURE PLANS

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ABSTRACT

The GHG-CCI project (http://www.esa-ghg-cci.org/) is one of several projects of the European Space Agency's (ESA) Climate Change Initiative (CCI). The goal of the CCI is to generate and deliver data sets of various satellite-derived Essential Climate Variables (ECVs) in line with GCOS (Global Climate Observing System) requirements. The "ECV Greenhouse Gases" (ECV GHG) is the global distribution of important climate relevant gases – namely atmospheric CO_2 and CH_4 - with a quality sufficient to obtain information on regional CO_2 and CH_4 sources and sinks. The main goal of GHG-CCI is to generate long-term highly accurate and precise time series of global near-surface-sensitive satellite observations of CO_2 and CH_4, i.e., XCO_2 and XCH_4, starting with the launch of ESA's ENVISAT satellite. These products are currently retrieved from SCIAMACHY/ENVISAT (2002-2012) and TANSO-FTS/GOSAT (2009-today) nadir mode observations in the near-infrared/shortwave-infrared spectral region. In addition, other sensors (e.g., IASI and MIPAS) and viewing modes (e.g., SCIAMACHY solar occultation) are also considered and in the future also data from other satellites. The GHG-CCI data products and related documentation are freely available via the GHG-CCI website and yearly updates are foreseen. Here we present an overview about the latest data set (Climate Research Data Package No. 2 (CRDP#2)) and summarize key findings from using satellite CO_2 and CH_4 retrievals to improve our understanding of the natural and anthropogenic sources and sinks of these important atmospheric greenhouse gases. We also shortly mention ongoing activities related to validation and initial user assessment of CRDP#2 and future plans.

1. INTRODUCTION

Carbon dioxide (CO_2) is the most important anthropogenic greenhouse gas responsible for global warming (*IPCC, 2013*). Despite its importance, our knowledge of the CO_2 sources and sinks is inadaquate and does not meet the needs for attribution, mitigation and the accurate prediction of future change (e.g., *Ciais et al., 2010*; *Canadell et al., 2010; IPCC, 2013; CEOS, 2014; Ciais et al., 2014*), and despite efforts to reduce CO_2 emissions, atmospheric CO_2 continues to increase with approximately 2 ppm/year (Fig. 1; *Le Quéré et al., 2014*).

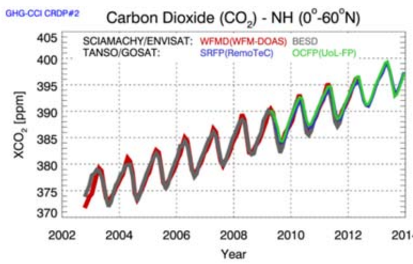

Fig. 1: GHG-CCI CRDP#2 XCO_2 Northern Hemisphere 2002-2013 (see Tab. 1 for details).

Figure 1 shows Northern Hemispheric XCO_2, i.e., the column-averaged CO_2 dry air mole fraction (in ppm), as retrieved from SCIAMACHY/ENVISAT and TANSO-FTS/GOSAT using four different GHG-CCI retrieval algorithms (see Sect. 2). Clearly visible is the CO_2 seasonal cycle - primarily caused by uptake and release of CO_2 by the terrestrial biosphere - and the atmospheric CO_2 increase with time, which is primarily caused by burning of fossil fuels (fraction not taken up by the terrestrial biosphere or the oceans). Also visible is the good agreement of the different GHG-CCI CRDP#2 XCO_2 data products. Perfect agreement is not expected due to different spatio-temporal sampling and different altitude sensitivities (averaging kernels).

Appropriate knowledge about the CO_2 sources and sinks is needed for reliable prediction of the future climate of our planet (*IPCC, 2013*). This is also true for methane (CH_4; e.g., *IPCC, 2013; Kirschke et al., 2013*). The goal of the GHG-CCI project (*Buchwitz et al., 2013a*), which is one of several projects of ESA's Climate Change Initiative (CCI, *Hollmann et al., 2013*), is to generate global satellite-derived CO_2 and CH_4 data sets as needed to improve our understanding of the regional sources and sinks of these important atmospheric gases.

Global near-surface-sensitive satellite observations of CO_2 and CH_4 combined with inverse modeling yields information on the regional sources and sinks of these gases. The goal of the GHG-CCI project is to generate the Essential Climate Variable (ECV) Greenhouse Gases (GHG) as required by GCOS. The GCOS definition of this ECV is (*GCOS, 2011*): "Product Number A.8.1: Retrievals of greenhouse gases, such as CO_2 and CH_4, of sufficient quality to estimate regional sources and sinks".

Currently multi-year measurements from two satellite instruments can be used to retrieve information on CO_2 and CH_4 with sufficient near-surface-sensitivity: SCIAMACHY on ENVISAT (2002 - April 2012) (*Burrows et al., 1995*; *Bovensmann et al., 1999*) and TANSO-FTS on-board GOSAT (launched in 2009) (*Kuze et al., 2009*). Both instruments perform (or have performed) nadir observations in the near-infrared/short-wave-infrared (NIR/SWIR) spectral region covering the relevant absorption bands of CO_2, CH_4 and O_2 (needed to obtain the "dry-air column" used to compute GHG column-averaged dry-air mole fractions, i.e., XCO_2 (in ppm) and XCH_4 (in ppb)). These two instruments are therefore currently the two main sensors used within GHG-CCI. The corresponding retrieval algorithms are referred to as "ECV Core Algorithms" (ECAs) within GHG-CCI.

In addition, a number of other sensors are also used within GHG-CCI (e.g., MIPAS/ENVISAT and IASI/MetOp-A) as they provide additional constraints for atmospheric layers above the planetary boundary layer. The corresponding retrieval algorithms are referred to as "Additional Constraints Algorithms" (ACAs) within GHG-CCI.

Even moderate to strong CO_2 and CH_4 sources and sinks only result in quite small changes of the column-averaged mole fractions relative to their background concentration. High relative accuracy of the satellite retrievals is required because even very small (regional) biases can lead to significant errors of the inferred surface fluxes. One of the first activities within GHG-CCI was to establish the user requirements, e.g., in terms of required accuracy and precision of the different data products. The result of this activity was the initial version of the GHG-CCI User Requirements Document (URD) (*Buchwitz et al., 2011*), which has recently been updated (*Chevallier et al., 2014b*). Note that the GHG-CCI URD requirements are more detailed and often also more demanding compared to the GCOS requirements (*GCOS, 2011*).

The GHG-CCI data products and related documentation are freely available via the GHG-CCI website and yearly updates generated with improved retrieval algorithms and covering (where possible) longer time series are foreseen.

Here we present an overview about the latest data set - Climate Research Data Package No. 2 (CRDP#2) (Sect. 2) - and summarize key findings from using satellite CO_2 and CH_4 retrievals to improve our understanding of the natural and anthropogenic sources and sinks of these important greenhouse gases (Sect. 3). We also shortly mention ongoing activities related to the validation and initial user assessment of CRDP#2 and future plans (Sect. 4).

2. CLIMATE RESEARCH DATA PACKAGE 2 (CRDP#2)

In this section, we present an overview about the GHG-CCI CRDP#2. CRDP#2 consists of several satellite-derived CO_2 and CH_4 data products and related documentation (freely available from http://www.esa-ghg-cci.org -> CRDP (Data)).

Currently (mid March 2015) a preliminary unvalidated version of CRDP#2 is already publicly available. Validation and initial user assessments as conducted by the GHG-CCI validation team and Climate Research Group (CRG) are ongoing activities. The final validated data set is planned to be ready end of March 2015 (see Sect. 4 for details).

Via the GHG-CCI website also the previous data set CRDP#1 and related documentation is available. Note that for CRDP#2 an improved data format has been defined focusing on harmonization of the ECA products (*Buchwitz et al., 2014*). An overview about the various satellite-derived data products stored in the CRDP#2 data base is shown in Tab. 1 (for ECA products) and Tab. 2 (for ACA products).

Table 1 lists the GHG-CCI ECV core data products XCO_2 and XCH_4 as retrieved from SCIAMACHY/ENVISAT and TANSO-FTS/GOSAT. Note that more details for each product are available on the GHG-CCI website including spatio-temporal coverage, detailed documentation (e.g., Algorithm Theoretical Basis Documents (ATBDs)), point of contact information, information on data access, figures, etc.

As can be seen from Tab. 1 typically the same product (e.g., XCO_2 from SCIAMACHY) has been generated using different retrieval algorithms. We encourage users of our data products to make use of the fact that several different methods are available to generate a given product. This gives users the possibility to find out if important conclusions drawn by using one product are robust with respect to the method used to generate that product. This however may require significant effort and is therefore not always possible. For users who only want to use one product but do not know which one to choose, we aimed at defining one recommended "baseline product" generated with a baseline algorithm (see Tab. 1). The other products are called "alternative products". Note that the quality of an alternative product may be (at least on average) equivalent to the corresponding baseline product. Typically different methods have different strengths and weaknesses and therefore which product to use for a given application is expected to depend on the application. For our products we found (typically quite) small but potentially still significant differences between the baseline and the alternative products but have not yet always been able to clearly identify which of the products is better (e.g., due to the limited number of ground-based validation sites). For this reason we have not yet defined a baseline product for all products (see Tab. 1).

As can also be seen from Tab. 1, the XCH_4 algorithms / products are typically classified as "Full Physics" (FP) or "Proxy" (PR). The PR algorithms are using simultaneously retrieved CO_2 columns and model CO_2 columns to convert the retrieved methane columns (in molecules/area) to XCH_4 (in ppb), whereas the FP algorithms do not rely only modelled CO_2. The advantage of the PR algorithms is that scattering related errors (due to aerosols and clouds) cancel to a large extent when computing the CH_4 to CO_2 column ratio. As a consequence, the PR algorithms are typically simpler and faster and typically deliver a larger number of quality filtered (i.e., "good") observations. See, e.g., *Schepers et al., 2012*, for a discussion of XCH_4 FP and PR methods.

Note that we have also generated a merged XCO_2 product via the EMMA algorithm (*Reuter et al., 2013*) by combining the individual SCIAMACHY and GOSAT XCO_2 products. Currently however the EMMA CRDP#2 product covers only a limited time period (see Tab. 1). However, also a recently updated product (EMMA v2.0) is available via the GHG-CCI website covering 4 years. Within GHG-CCI the EMMA XCO_2 product is also used as a comparison tool for the individual products.

In line with the GHG-CCI user requirements (*Chevallier et al., 2014b*) the GHG-CCI ECA data products listed in Tab. 1 are (non-gridded) Level 2 products, i.e., they contain XCO_2 and XCH_4 values for each single observation along with information on time and location, uncertainty, quality flag, etc. (see *Buchwitz et al., 2014*, for details).

For illustration, seasonal averages of CRDP#2 products are shown in Fig. 2 for XCO_2 and Fig. 3 for XCH_4.

3. OVERVIEW SCIENTIFIC ACHIEVEMENTS

In this section a short overview is presented on scientific publications related to CO_2 and CH_4 satellite retrievals, which have been published during approximately the first four years of the GHG-CCI project (until mid March 2015). Focus is on publications related to GHG-CCI retrieval algorithms and corresponding data products and their use to address important scientific questions related to the natural and anthropogenic sources and sinks of CO_2 and CH_4. In this context also some other (non-GHG-CCI) publications are mentioned (in the References GHG-CCI-related publications are marked with (*); currently the number of peer-reviewed publications with GHG-CCI/CCI funding explicitly acknowledged is 38).

GHG-CCI CRDP#2: ECV Core Algorithm (ECA) Products				
Algorithm / Product ID (version)	**Product**	**Sensor Satellite**	**Algorithm Institute**	**Comment (Reference)**
CO2_SCI_BESD (v02.00.08)	XCO_2	SCIAMACHY ENVISAT	BESD IUP	*SCIAMACHY XCO_2 baseline product (Reuter et al., 2011)*
CO2_SCI_WFMD (v3.8)	XCO_2	SCIAMACHY ENVISAT	WFM-DOAS IUP	*SCIAMACHY XCO_2 alternative product (Schneising et al., 2011)*
CO2_GOS_OCFP (v5.1)	XCO_2	TANSO GOSAT	UoL-FP UoL	*GOSAT XCO_2 product (baseline not yet decided) (Cogan et al., 2012)*
CO2_GOS_SRFP (v2.3.6)	XCO_2	TANSO GOSAT	RemoTeC SRON/KIT	*GOSAT XCO_2 product (baseline not yet decided) (Butz et al., 2011)*
CO2_EMMA (v1.7)	XCO_2	Merged SCIA and GOSAT	EMMA IUP (lead)	*Short time period only (6.2009-7.2010) (Reuter et al., 2013) (*)*
CH4_SCI_WFMD (v3.7)	XCH_4	SCIAMACHY ENVISAT	WFM-DOAS IUP	*SCIAMACHY XCH_4 proxy product (baseline not yet decided) (Schneising et al., 2011)*
CH4_SCI_IMAP (v7.0)	XCH_4	SCIAMACHY ENVISAT	IMAP SRON/JPL	*SCIAMACHY XCH_4 proxy product (baseline not yet decided) (Frankenberg et al., 2011)*
CH4_GOS_OCPR (v5.1)	XCH_4	TANSO GOSAT	UoL-PR UoL	*GOSAT XCH_4 proxy baseline product (Parker et al., 2011)*
CH4_GOS_SRPR (v2.3.6)	XCH_4	TANSO GOSAT	RemoTeC SRON/KIT	*GOSAT XCH_4 proxy alternative product (Butz et al., 2010)*
CH4_GOS_SRFP (v2.3.6)	XCH_4	TANSO GOSAT	RemoTeC SRON/KIT	*GOSAT XCH_4 full physics baseline product (Butz et al., 2011)*
Details (temporal coverage, etc.): http://www.esa-ghg-cci.org -> CRDP (Data)				

Tab. 1: Overview GHG-CCI core ("ECA") data products. (*) The latest version, EMMAv2.0, covers 4 years and is also available on the GHG-CCI website.

GHG-CCI CRDP#2: Additional Constraints Algorithm (ACA) Products				
Algorithm / Product ID	**Product**	**Sensor**	**Algorithm / Institute**	**Reference**
CO2_AIR_NLIS (*)	Mid/upper tropospheric column	AIRS	NLIS / LMD	*Crevoisier et al., 2004*
CO2_IAS_NLIS	Mid/upper tropospheric column	IASI	NLIS / LMD	*Crevoisier et al., 2009*
CO2_ACE_CLRS	Upper trop. / stratospheric profile	ACE-FTS	CLRS / LMD	*Foucher et al., 2009*
CH4_IAS_NLIS	Upper trop. / stratospheric profile	IASI	NLIS / LMD	*Crevoisier et al., 2013*
CH4_MIP_IMK (*)	Upper trop. / stratospheric profile	MIPAS	MIPAS / KIT-IMK	*Laeng et al., 2014*
CH4_SCI_ONPD	Stratospheric profile	SCIAMACHY	ONPD / IUP	*Noël et al., 2011*
CO2_SCI_ONPD	Stratospheric profile	SCIAMACHY	ONPD / IUP	*Noël et al., 2011*
Details (temporal coverage, etc.): http://www.esa-ghg-cci.org -> CRDP (Data)				

Tab. 2: Overview GHG-CCI ACA products providing information on CO_2 and CH_4 in atmospheric layers above the planetary boundary layer. (*) CRDP#1 product (no update for CRDP#2).

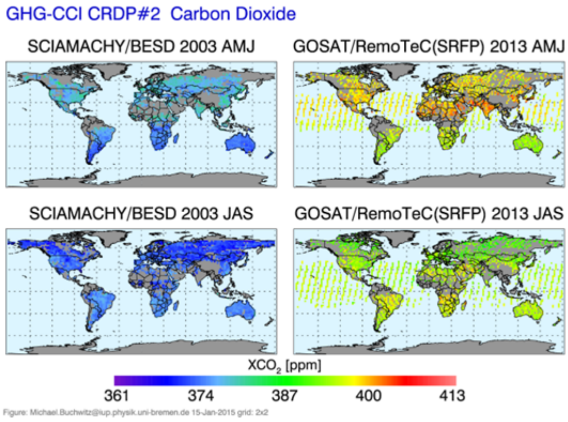

Fig.2: GHG-CCI CRDP#2 XCO_2 products.

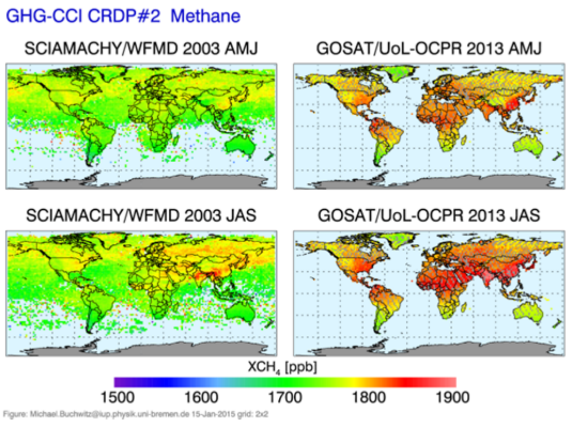

Fig.3: GHG-CCI CRDP#2 XCH_4 products.

The list of all GHG-CCI publications is available via the GHG-CCI website (http://www.esa-ghg-cci.org -> Publications), where also links to the publications are given. Please visit this website for the most up-to-date list of all GHG-CCI publications. Several publications are addressing improvements of the retrieval algorithms, e.g.,

- *Reuter et al., 2011*, presents first results from the application of the advanced BESD algorithm (*Reuter et al., 2010*) to SCIAMACHY XCO_2 retrievals. BESD has been developed to improve the accuracy and precision compared to the simpler but much faster WFMD algorithm and as shown in, e.g., *Dils et al., 2014*, this goal has been achieved.
- The WFMD XCO_2 retrieval algorithm has also been significantly improved during GHG-CCI as shown in *Heymann et al., 2012a, 2012b,* and *Schneising et al., 2011, 2012,* and used to address important CO_2 science issues as described below (e.g., *Schneising et al., 2013, 2014a*). This is also true for the WFMD XCH_4 retrieval algorithm (*Schneising et al., 2011, 2012, 2014b*).
- GHG-CCI GOSAT XCO_2 and XCH_4 algorithm improvements are also reported in a number of publications: *Butz et al., 2011, Cogan et al., 2012, Guerlet et al., 2013a, 2013b, Parker et al., 2011*, and *Schepers et al., 2012*.
- Recently, *Heymann et al., 2015*, has used the BESD algorithm to retrieve XCO_2 from GOSAT. This new product is being generated within the framework of the European MACC project (https://www.gmes-atmosphere.eu/), the predecessor of the upcoming operational European Copernicus Atmosphere Monitoring Service (CAMS), and not further discussed here.
- Retrieval algorithm related aspects for ACA products are also presented in a number of publications (e.g., *Noël et al., 2011, Laeng et al., 2014*).

Some publications are addressing related aspects, e.g.,

- *Dils et al., 2014*, presents a detailed validation of the initial ("Round Robin exercise", see *Buchwitz et al., 2013a*) GHG-CCI data products by comparisons with ground-based Total Carbon Column Observing Network (TCCON) (*Wunch et al., 2011*) XCO_2 and XCH_4 retrievals.
- Specific aspects related to the validation of the satellite XCH_4 products are presented in *Sussmann et al., 2011, 2013.*
- *Reuter et al., 2013*, developed the ensemble algorithm EMMA which uses the individual satellite Level 2 XCO_2 data products as input data to generate a new Level 2 data product where essentially outliers have been identified and removed to generate a potentially more robust "median product" exploiting the availability of an ensemble of individual products exists generated with algorithms each having different strengths and weaknesses. The EMMA method is used within GHG-CCI as a comparison tool for the individual global products. The advantage here is that products can be compared with the median product without relying on model simulations and without being limited to (sparse) ground-based validation sites. Note that for EMMA not only the European GHG-CCI data products are being used but also non-European GOSAT products generated in Japan at NIES (*Yoshida et al., 2013*, *Oshchepkov et al., 2011, 2013*) and the NASA ACOS product (*O'Dell et al., 2012*).
- *Reuter et al., 2012a*, used the XCO_2 retrieval algorithm BESD to study to what extent information on CO_2 isotopologues can be retrieved from GOSAT data and in *Reuter et al., 2012b*, a simple model ("SECM") is described which can be (and is) used to obtain atmospheric CO_2 background concentrations to be used as *a priori* information for satellite XCO_2 retrievals.

The main goal of the GHG-CCI project is to generate satellite-derived data products required to improve our knowledge on the sources and sinks of CO_2 and CH_4. Having delivered improved data products, these are then combined with knowledge of wind fields, with sophisticated atmospheric models or data assimilation techniques to determine, assess and constrain surface fluxes of CO_2 and CH_4. Relevant publications are described briefly below starting with publications addressing natural CO_2 fluxes:

- Using global GOSAT XCO_2 retrievals *Basu et al., 2013*, presented first CO_2 surface flux inverse modeling results for various regions. Their analysis suggests a reduced global land sink and a shift of the carbon uptake from the tropics to the extra-tropics. Their results also imply that Europe is a stronger carbon sink than expected.
- *Chevallier et al., 2014a*, used an ensemble of inversion methods and GOSAT XCO_2 retrievals to also derive regional CO_2 surface fluxes. They also found a significantly larger European carbon sink. They conclude that the derived sink is unrealistically large and they argue that this may be due to modelling issues related to long-range transport modelling and biases of the satellite retrievals. In particular they argue that errors of the satellite data outside of Europe may adversely influence the European results.
- *Reuter et al., 2014a*, investigated this European carbon sink issue in detail using an ensemble of SCIAMACHY and

GOSAT XCO_2 data products and a new inversion method which is not, or significantly less, sensitive to the potential issues discussed in *Chevallier et al., 2014a*. For example, *Reuter et al., 2014a,* only used satellite XCO_2 retrievals over Europe to rule out that non-European satellite data adversely influence the results related to the European carbon sink and they also only used short-term (days) transport modelling to minimize long-range transport errors. *Reuter et al., 2014a,* also performed several sensitivity tests to investigate and ensure the robustness of their results and to establish a reliable error budget. Based on an extensive analysis they conclude: "We show that the satellite-derived European terrestrial carbon sink is indeed much larger (1.02 +/- 0.30 GtC/year in 2010) than previously expected". The value they derived is larger compared to earlier inversion estimates using in-situ observations of 0.47 +/- 0.50 ("LSCE-39-insitu inversion") or 0.42 +/- 0.25 ("UoE-insitu") GtC/year for 2010 (*Chevallier et al., 2014a*), or 0.40 +/- 0.42 GtC/year for 2001-2004 (*Peylin et al, 2013*), which is reported in the recent IPCC report (*IPCC, 2013*) (see also: http://www.esa.int/Our_Activities/Observing_the_Earth/Is_Europe_an_underestimated_sink_for_carbon_dioxide). The disagreement with bottom-up estimates is even larger and significant: *Schulze et al., 2009,* report 0.235 +/- 0.05 GtC/year between 2000 and 2005.

- The findings of *Reuter et al., 2014a,* stimulated additional research (*Feng et al., 2015*).
- Focussing on Canadian and Siberian boreal forests, *Schneising et al., 2011,* computed longitudinal XCO_2 gradients from SCIAMACHY XCO_2 retrievals during the vegetation growing season over Canadian and Siberian boreal forests and compared the gradients with outputs from NOAA's CO_2 inversion system CarbonTracker (*Peters et al., 2007*). They found good agreement for the total boreal region and for inter-annual variations. For the individual regions, however, they found systematic differences suggesting a stronger Canadian boreal forest growing season CO_2 uptake and a weaker Siberian forest uptake compared to CarbonTracker.
- Focussing on hemispheric data and on carbon-climate feedbacks, *Schneising et al., 2013b,* used SCIAMACHY XCO_2 to study aspects related to the terrestrial carbon sink by looking at co-variations of XCO_2 growth rates and seasonal cycle amplitudes with near-surface temperature. They found XCO_2 growth rate changes of 1.25+/-0.32 ppm/year/K (approximately 2.7+/-0.7 GtC/year/K; indicating less carbon uptake in warmer years, i.e., a positive carbon-climate feedback) for the Northern Hemisphere in good agreement with CarbonTracker.
- *Reuter et al., 2013,* computed CO_2 seasonal cycle amplitudes using various satellite XCO_2 data products (using GHG-CCI products but also GOSAT XCO_2 products generated in Japan at NIES (*Yoshida et al., 2013, Oshchepkov et al., 2011, 2013*) and the NASA ACOS product (*O'Dell et al., 2012*)) and compared the amplitudes with TCCON and CarbonTracker. They found that the satellite products typically agree well with TCCON but they found significantly lower amplitudes for CarbonTracker suggesting that CarbonTracker underestimates the CO_2 seasonal cycle amplitude by approx. 1.5+/-0.5 ppm (see also *Buchwitz et al., 2013a,* for a discussion of these findings).
- *Guerlet et al., 2013b,* analyzed GOSAT XCO_2 retrievals focusing on the Northern Hemisphere. They identified a reduced carbon uptake in the summer of 2010 and found that this is most likely due to the heat wave in Eurasia driving biospheric fluxes and fire emissions. Using a joint inversion of GOSAT and surface data, they estimated an integrated biospheric and fire emission anomaly in April–September of 0.89±0.20 PgC over Eurasia. They found that inversions of surface measurements alone fail to replicate the observed XCO_2 inter-annual variability (IAV) and underestimate emission IAV over Eurasia. They highlighted the value of GOSAT XCO_2 in constraining the response of land-atmosphere exchange of CO_2 to climate events.
- *Basu et al., 2014,* studied seasonal variations of CO_2 fluxes during 2009-2011 over Tropical Asia using GOSAT, CONTRAIL and IASI data. They found an enhanced source for 2010 and concluded that this is likely due to the biosphere response to above-average temperatures in 2010 and unlikely due to biomass burning emissions.
- *Parazoo et al., 2013,* used GOSAT XCO_2 and solar induced chlorophyll fluorescence (SIF) retrievals to better understand the carbon balance of southern Amazonia.
- *Ross et al., 2013,* used GOSAT data to obtain information on wildfire CH_4:CO_2 emission ratios.
- For flux inversions not only the retrieved greenhouse gas values are relevant but also their error statistics, in particular the reported uncertainties. *Chevallier and O'Dell, 2013,* analyzed this aspect in the context of CO_2 flux inversions using GOSAT XCO_2 retrievals.

Despite the fact that none of the existing satellite missions has been optimized to obtain information on anthropogenic CO_2 emissions this important aspect has been addressed in several recent publications using existing satellite XCO_2 products:

- *Schneising et al., 2013a,* present an assessment of the satellite data over major anthropogenic CO_2 source regions. They used a multi-year SCIAMACHY XCO_2 data set and compared the regional XCO_2 enhancements and trends with the emission inventory EDGAR v4.2 (*Olivier et al., 2012*). They found no significant trend for the Rhine-Ruhr area in central Europe and the US East Coast but a significantly increasing trend for the Yangtze River Delta in China of about 13+/-8%/year, in agreement with EDGAR (10+/-1%/year).
- *Reuter et al., 2014,* studied co-located SCIAMACHY XCO_2 and NO_2 retrievals over major anthropogenic source regions. For East Asia they found increasing emissions of NO_x (+5.8%/year) and CO_2 (+9.8%/year), i.e., decreasing emissions of NO_x relative to CO_2 indicating that the recently installed and renewed technology in East Asia, such as power plants and transportation, is cleaner in terms of NO_x emissions than the old infrastructure, and roughly matches relative emission levels in North America and Europe (see also: http://www.esa.int/Our_Activities/Observing_the_Earth/Space_for_our_climate/Good_and_bad_news_for_our_atmosphere).

Methane:

SCIAMACHY data have already been extensively used to improve our knowledge on regional methane emissions prior to the start of the GHG-CCI project (e.g., *Bergamaschi et al., 2009*). A more recent research focus has been to investigate the unexpected renewed atmospheric methane increase since 2007 using ground-based and satellite data (e.g., *Rigby et al., 2008, Dlugokencky et al., 2009, Bergamaschi et al., 2009, 2013, Schneising et al., 2011, Frankenberg et al., 2011, Sussmann et al., 2012, Crevoisier et al., 2013*). Based on an analysis of SCIAMACHY year 2003-2009 retrievals an increase of 7-9 ppb/year (0.4-0.5%/year) has been found with the largest increases in the tropics and northern mid latitudes (*Schneising et al., 2011*) but a particular region responsible for the increase has not been identified (*Schneising et al., 2011; Frankenberg et al., 2011*). *Bergamaschi et al., 2013,* used SCIAMACHY retrievals and NOAA surface data for 2003-2010 and inverse modelling to address this aspect. They concluded that the main reason for the increase are increasing anthropogenic emissions with wetland and biomass burning emissions being responsible for most of the inter-annual variations.

- Methane emission estimates have also been obtained from GOSAT as shown in a number of recent publications, e.g., *Fraser et al., 2013, 2014, Monteil et al., 2013, Cressot et al., 2014*, *Alexe et al., 2015*. In these studies often CH_4 retrievals from several satellites have been used (as well as NOAA data), e.g., *Monteil et al., 2013*, and *Alexe et al., 2015*, used SCIAMACHY and GOSAT retrievals and *Cressot el al., 2014*, used GOSAT, SCIAMACHY and IASI.
- Several publications focused on (relatively localized) methane sources in the United States: For example, *Schneising et al., 2014*, analyzed SCIAMACHY data over major US "fracking" regions and quantified methane emissions and leakage rates. For two of the fastest growing production regions in the US, the Bakken and Eagle Ford formations, they estimated that emissions increased by 990±650 $ktCH_4$/year and 530±330 $ktCH_4$/year between the periods 2006–2008 and 2009–2011. Relative to the respective increases in oil and gas production, these emission estimates correspond to leakages of 10.1%±7.3% and 9.1%±6.2% in terms of energy content, calling immediate climate benefit into question and indicating that current inventories likely underestimate the fugitive emissions from Bakken and Eagle Ford. Others also used SCIAMACHY data over the US to identify and quantify localized anthropogenic methane emission sources (*Kort et al., 2014, Wecht et al., 2014*).
- The SCIAMACHY XCH_4 retrievals have also been used to improve chemistry-climate models (*Shindell et al., 2014, Hayman et al., 2014*).

4. ONGOING ACTIVITIES AND FUTURE PLANS

Currently (mid March 2015) a preliminary unvalidated version of CRDP#2 is available via the GHG-CCI website (http://www.esa-ghg-cci.org -> CRDP (Data)) as validation and initial user assessments as conducted by the GHG-CCI validation team and Climate Research Group (CRG) are ongoing activities. The validation results will be reported in a document called "Product Validation and Intercomparison Report, version 3.x" (PVIRv3.x) and the user assessments will be reported in the "Climate Assessment Report, version 2.x" (CARv2.x). PVIRv3.x will be ready end of March 2015 and CARv2.x in April 2015 and both documents will be made publicly available along with the final validated CRDP#2 data products via the GHG-CCI website. These documents are updates of the corresponding CRDP#1 documents PVIRv2.0 (*Notholt et al., 2013*) and CARv1.1 (*Chevallier et al., 2013*).

Based on the outcome of the quality assessments the retrieval algorithms will be further improved and the satellite data will be reprocessed (if necessary) and, where possible, the time series will be extended. Yearly updates are foreseen and it is planned to release CRDP#3 in April 2016. GHG-CCI retrieval experts are also members of the OCO-2 Science Team and involved in the development of retrieval algorithms for Sentinel-5-Precursor and the data products of these sensors will also be considered by GHG-CCI. For OCO-2 it is initially planned to perform detailed comparisons to determine the consistency of the XCO_2 data products and to perform initial retrievals.

GHG-CCI team members are also involved in the specification of future GHG satellites, in particular CarbonSat (*Bovensmann et al., 2010, Buchwitz et al., 2013b*). CarbonSat, if selected for ESA's Earth Explorer 8 satellite, will continue the time series of greenhouse gas observations from space presented in this manuscript but will also address many important new aspects which cannot (or only with severe limitations) be addressed with other existing or planned satellites in particular the detection of localized CO_2 and CH_4 sources and the quantification of their emissions. Like SCIAMACHY, GOSAT and OCO-2, sun induced chlorophyll fluorescence, SIF, will be a secondary data product from CarbonSat (*Buchwitz et al., 2013b*) suitable to obtain Gross Primary Production (GPP; e.g., *Parazoo et al., 2013*, and references given therein) and for investigating the impact of stress on vegetation and the CO_2 uptake at the few km^2 spatial resolution scale of CarbonSat. The main goal of CarbonSat is to advance our knowledge on the natural and man-made sources and sinks of the two most important anthropogenic greenhouse gases carbon dioxide and methane from the global via the sub-continental to the local scale. CarbonSat will be the first satellite mission to image small scale emission hot spots of CO_2 (e.g., cities, volcanoes, industrial areas) and CH_4 (e.g., fossil fuel production, landfills, seeps) and to quantify their emissions and discriminate them from surrounding biospheric fluxes. In this context see also *Ciais et al., 2014*, and *CEOS, 2014*, for an overview about current capabilities and limitations and future needs for establishing a global carbon observing system.

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