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THE GREENHOUSE GAS PROJECT OF ESA'S CLIMATE CHANGE INITIATIVE (GHG-CCI): PHASE 2 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) 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. Here we present an overview about the latest data set (Climate Research Data Package No. 2 (CRDP#2)) focusing on the GHG-CCI core products and present a short overview about GHG-CCI-related achievements in terms of scientific publications.

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, 2014; Canadell et al., 2010; IPCC, 2013; CEOS, 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). 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., 2015a), 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 Essential Climate Variable (ECV) Greenhouse Gases (GHG) data sets 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".

Figure 1 (a) 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). Corresponding XCO_2 and XCH_4 maps are shown in Fig. 1 (b).

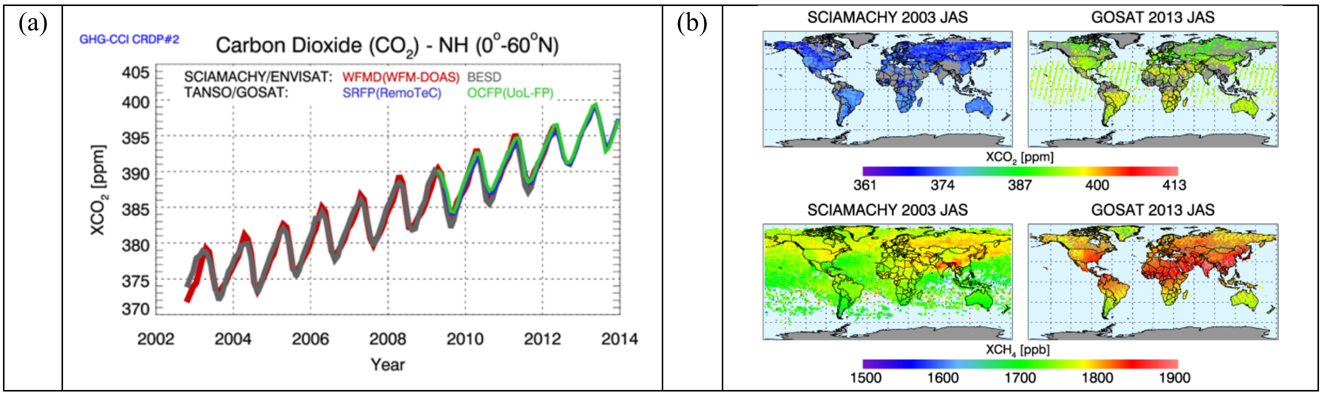

Fig. 1: (a) GHG-CCI CRDP#2 XCO_2 Northern Hemisphere 2002-2013 (see Tab. 2 for details). (b) GHG-CCI CRDP#2 XCO_2 (top) and XCH_4 (bottom) maps for July-September 2003 (left) and 2013 (right).

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 shortly summarize some key scientific achievements (Sect. 3). For the latter however we primarily have to limit ourselves to the presentation of a list of scientific publications where the GHG-CCI CO_2 and CH_4 data sets have been used to improve our understanding of the natural and anthropogenic sources and sinks of these important greenhouse gases. We also shortly mention ongoing activities 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)). 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, providing a general overview for ECA and ACA products, and Tab. 2, providing details on ECA products.

Table 2 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. 2 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. 2). 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. 2).

As can also be seen from Tab. 2, 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 on 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 Tabs. 1 and 2). 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. 2 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). Validation results for CRDP#2 are reported in the "Product Validation and Intercomparison Report, version 3.2" (PVIRv3.2, Buchwitz et al., 2015b, see also Tab. 3) and initial user assessments as carried out by the GHG-CCI Climate Reserch Group (CRG) are reported in the "Climate Assessment Report, version 2" (CARv2, Chevallier et al., 2015). These documents are updates of the corresponding CRDP#1 documents PVIRv2.0 (Notholt et al., 2013) and CARv1.1 (Chevallier et al., 2013).

3. OVERVIEW GHG-CCI SCIENTIFIC ACHIEVEMENTS

The GHG-CCI data products of CRDP#1 and CRDP#2 have been used to address a number of scientific carbon and climate issues as can be seen from section REFERENCES (note that all GHG-CCI-related publications are marked with (*)). A detailed overview on all GHG-CCI peer-reviewed publications (available until March 2015) is given in Buchwitz et al., 2015c, which is also available from the GHG-CCI website. As can be seen from section REFERENCES in total 38 peer-reviewed publications exist (May 2015), where GHG-CCI funding has been explicitly acknowledged. 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. Here we would like to highlight only two publications:

Reuter et al., 2014a, used an ensemble of satellite XCO_2 data products and a new inversion method to quantify the strength of the European carbon sink. Their results indicate that this sink is likely larger than hitherto known. See also the related ESA webstory "Is Europe an underestimated sink for carbon ?" (http://www.esa.int/Our_Activities/Observing_the_Earth/Is_Europe_an_underestimated_sink_for_carbon_dioxide)

Reuter et al., 2014b, 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-related sources, is cleaner in terms of NO_x emissions per amount of fossil fuel burned than the old infrastructure, and roughly matches relative emission levels in North America and Europe. (http://www.esa.int/Our_Activities/Observing_the_Earth/Space_for_our_climate/Good_and_bad_news_for_our_atmosphere)

GHG-CCI Climate Research Data Package (CRDP#2)															
Main Product ID	Product (Level 2, mole fractions)	Years processed													
		2002	03	04	05	06	07	08	09	10	11	12	13	14	15
GHG-CCI Core Products: ECV Core Algorithm (ECA) Products															
XCO2_SCIA	XCO_2														
XCH4_SCIA	XCH_4														
XCO2_GOSAT	XCO_2														
XCH4_GOSAT	XCH_4														
XCO2_EMMA	XCO_2														
Additional Constraints Algorithm (ACA) Products															
CO2_IASI	CO_2 (1)														
CH4_IASI	CH_4 (1)														
CH4_SCIAOCC	CH_4 (2)														
CO2_SCIAOCC	CO_2 (2)														
CO2_ACEFTS	CO_2 (2)														
CH4_MIPAS	CH_4 (2)														
CO2_AIRS	CO_2 (1)														

Comments:

ACA products:
(1) Mid / upper tropospheric column
(2) Upper tropospheric / stratospheric profile

CRDP#2
Also available

ECA Algorithms for column-averaged dry air mole fractions:

XCO2_SCIA: BESD, WFMD
XCH4_SCIA: WFMD, IMAP
XCO2_GOSAT: SRFP (RemoTeC), OCFP (UoL-FP)
XCH4_GOSAT: SRFP & SRPR (RemoTeC), OCPR (UoL-PR)
XCO2_EMMA: Various (SCIA & GOSAT merged)

Tab. 1: Overview CRDP#2. For details on the core algorithms see Tab. 2.

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. 2: Overview GHG-CCI core ("ECA") data products. (*) The latest version, EMMAv2.0, covers 4 years and is also available on the GHG-CCI website. (§) Improved v5.2 products also available on GHG-CCI website.

<table>
<tr><th colspan="4">GHG-CCI CRDP#2: Comparison of ECA products with GCOS Requirements</th></tr>
<tr><th>Variable (*)</th><th>Resolution</th><th>Accuracy</th><th>Stability</th></tr>
<tr><td>XCO_2</td><td rowspan="3">Temporal: GCOS: 4 hours Achieved: Days

Note: No existing nor any planned mission meets the GCOS temporal resolution requirement.

Spatial: GCOS: 5-10 km Achieved($): 10 km

($) for GOSAT. SCIAMACHY: 30x60 km^2.

Note: GCOS requirements are target (maximum) requirements but URD requirements listed here are threshold (minimum) requirements.</td><td>GCOS: < 1 ppm

URD(#): < 0.5 ppm

Achieved(#): 0.4-0.9 ppm(?)

(?) Depending on sensor, time period and assessment method</td><td>GCOS: < 0.2 ppm/yr

URD: < 0.5 ppm/yr

Achieved: << 0.5 ppm/yr(+)

(+) Derived trends not significant</td></tr>
<tr><td>XCH_4</td><td>GCOS: < 10 ppb

URD(#): < 10 ppb

Achieved(#): 3-8 ppb(§)

(§) for GOSAT; for SCIAMACHY 8-15 ppb depending on time period (degradation after Oct. 2005)</td><td>GCOS: < 2 ppb/yr

URD: < 10 ppb/yr

Achieved: < 4 ppb/yr(!)

(!) Derived trends mostly not significant but note (§§)</td></tr>
<tr><td></td><td colspan="2">(#) Relative accuracy (i.e., excluding possible constant global offset) estimated by comparison with TCCON ground-based observations; TCCON accuracy (1-sigma): 0.4 ppm for XCO_2 and 3.5 ppb for XCH_4

(§§) Stability as used here quantifies only long-term drift and therefore does not capture certain “jumps” due to detector issues as observed when analyzing the global SCIAMACHY XCH_4 (e.g., IMAP product mid 2010)</td></tr>
<tr><td colspan="4">(*) Requirements for column-averaged mole fractions (= air column normalized vertical GHG columns) as required by URD; it is assumed here that this corresponds to GCOS variables „Tropospheric CO_2 column“ and „Tropospheric CH_4 column“</td></tr>
<tr><td colspan="4"><u>References:</u> GCOS (GCOS-154): GCOS, 2011; URD: Chevallier et al., 2015

<u>Definition:</u> ECV GHG (GCOS-154): Product A8.1: Retrievals of CO_2 and CH_4 of sufficient quality to estimate regional sources and sinks</td></tr>
</table>

Tab. 3: Comparison of the characteristics of the GHG-CCI CRDP#2 core (ECA) products with user requirements. From: *Buchwitz et al., 2015b* (PVIRv3.2).

4. ONGOING ACTIVITIES AND FUTURE PLANS

Currently (May 2015) GHG-CCI team members are working on further improving the retrieval algorithms to be used for re-processing of the satellite data. The next version of the GHG-CCI Climate Research Data Package, CRDP#3, will be released in April 2016 (including documentation on validation (PVIR) and initial user assessments (CAR)).

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., 2013). 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., 2013) which can be linked to 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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Note: (*) indicates publications with acknowledged GHG-CCI funding

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