The GHG-CCI project of ESA's Climate Change Initiative: Overview and Status

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ABSTRACT

The GHG-CCI project (http://www.esa-ghg-cci.org) is one of several projects of ESA's Climate Change Initiative (CCI, http://www.esa-cci.org/), which will deliver various Essential Climate Variables (ECVs). The goal of GHG-CCI is to generate global satellite-derived data sets of the two most important anthropogenic greenhouse gases (GHG) carbon dioxide (CO_2) and methane (CH_4) with a quality suitable to derive information on regional CO_2 and CH_4 surface sources and sinks. A good understanding of GHG sources and sinks is a pre-requisite for reliable climate prediction. The GHG-CCI core ECV data products are near-surface sensitive column-averaged dry air mole fractions of CO_2 and CH_4, denoted XCO_2 and XCH_4, retrieved from SCIAMACHY/ENVISAT and TANSO-FTS/GOSAT. Other satellite instruments such as IASI and MIPAS are also used as they provide additional information about the two GHGs. Here we present an overview of the GHG-CCI project, which started in September 2010, focusing on XCO_2.

1. INTRODUCTION

Carbon dioxide (CO_2) is the most important anthropogenic greenhouse gas causing global warming [12]. Despite its importance our knowledge about CO_2 sources and sinks has significant gaps and despite efforts to reduce CO_2 emissions atmospheric CO_2 continues to increase with approximately 2 ppm/year (Fig. 1). Appropriate knowledge about the CO_2 sources and sinks is needed for reliable prediction of the future climate of our planet [12]. This is also true for methane (CH_4). However, in contrast to CO_2, atmospheric methane levels were rather stable during several years prior to 2007 but continued to increase again in recent years (Fig. 2). It is neither well understood why methane was stable before 2007 nor why it started to increase in 2007 and later years (at a rate of approximately 7-8 ppb/year) (see [8,21] and references given therein).

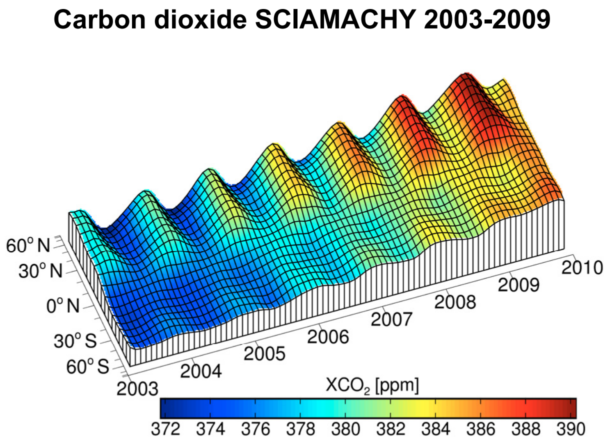

Fig. 1: Latitude – time series of column-averaged CO_2 mole fraction, XCO_2, during 2003-2009, as retrieved from SCIAMACHY/ENVISAT using the WFM-DOAS retrieval algorithm [21,22]. Clearly visible is the CO_2 seasonal cycle - primarily caused by uptake and release of CO_2 by the terrestrial biosphere - and the atmospheric CO_2 increase with time, which is primarily caused by burning of fossil fuels.

Global satellite observations of near-surface sensitive CO_2 and CH_4 variations can help to better understand the sources and sinks of these two important greenhouse gases. This typically requires sophisticated (inverse) modeling but important information such as the identification of major source regions can also be obtained by, for example, visual inspection of maps of the satellite data products (e.g., Fig. 3).

The goal of the GHG-CCI project is to generate the Essential Climate Variable (ECV) Greenhouse Gases (GHG) defined as follows [9]:

- "Product A.9: Global distribution of greenhouse gases, as methane and carbon dioxide, of sufficient quality to estimate regional sources and sinks".

Measurements with global coverage are only available from satellites. In order to get information on regional GHG sources and sinks it is required to use satellite data which are sensitive to near-surface GHG concentration variations.

Currently only two satellite instruments are in orbit which fulfill this requirement: SCIAMACHY on ENVISAT (launched in 2002) [1] and TANSO on-board GOSAT (launched in 2009) [13]. Both instruments perform 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 dry-air column averaged mole fractions such as XCO_2). These two instruments are therefore the two main sensors used within GHG-CCI.

In addition, a number of other sensors are also used within GHG-CCI (e.g., MIPAS/ENVISAT and IASI/METOP) as they provide additional constraints for atmospheric layers above the planetary boundary layer.

Even moderate to strong CO_2 and CH_4 sources and sinks only result in quite small changes of the column-averaged mole fractions (or mixing ratios) relative to their background concentration. High relative accuracy of the satellite retrievals is required because even very small (regional) biases would lead to significant errors of the inferred surface fluxes [2]. One of the first activities within GHG-CCI was to establish the user requirements, e.g., in terms of required accuracy and precision (Sect. 3.1).

The focus of the (ongoing) first two years of the GHG-CCI project is to improve existing retrieval algorithms in order to improve the accuracy of the retrieved GHG data products. Several algorithms per data product have been further developed and iteratively improved in competition. This activity is referred to as "Round Robin" (RR) exercise within the CCI and carried out by each of the (currently) 13 ECV projects. For GHG-CCI the RR phase covers the first two years of this project (Sep. 2010 – Aug. 2012). The status of this activity is shortly described in Sect. 3.2 and 4.

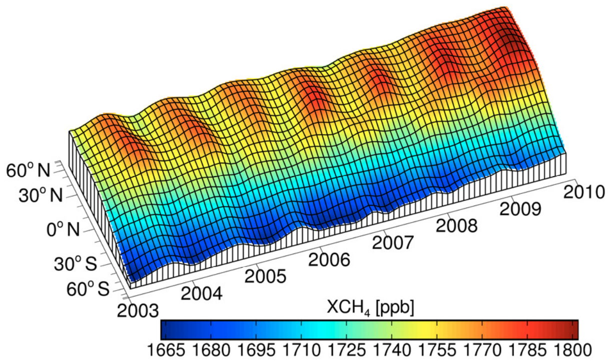

Fig. 2: Latitude – time series of column-averaged CH_4 mole fraction, XCH_4, during 2003-2009, as retrieved from SCIAMACHY/ENVISAT using the WFM-DOAS retrieval algorithm [21]. Clearly visible is the seasonal cycle and the recent CH_4 increase.

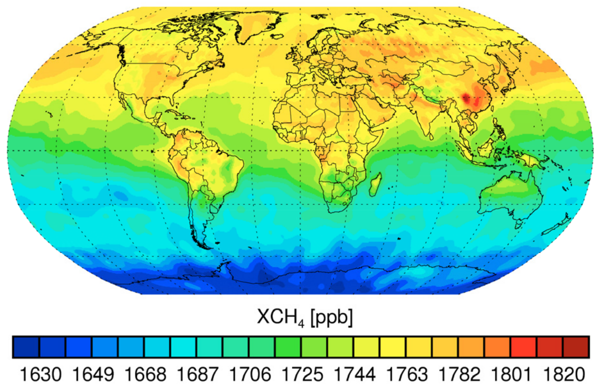

Fig. 3: Global map of methane obtained by averaging all SCIAMACHY/WFM-DOAS XCH_4 retrievals obtained during 2003-2009 [21]. Clearly visible are major source regions such as China (e.g., rice and wetland emissions). Most of the methane sources (wetlands, rice paddies, coal, gas and oil production, ruminants, etc.) are located in the northern hemisphere (NH). Methane mixing ratios are therefore typically higher over the NH compared to the southern hemisphere.

This manuscript is structured as follows: In Sect. 2 an overview about the GHG-CCI project is given. The project status is reported in Sect. 3 and 4. The user requirements are reported in Sect. 3.1 and information about the RR exercise is given in Sect. 3.2. Section 4 presents more details on the ongoing activities to generate a high quality satellite derived XCO_2 data product using an ensemble of data products generated with different individual algorithms, which all appear to have different strengths but also different weaknesses. Finally, an outlook is given in Sect. 5.

2. GHG-CCI PROJECT OVERVIEW

The GHG-CCI project covers all aspects needed to generate the ECV GHG and to assess the quality and the usefulness of the satellite-derived data products (Fig. 4). As shown in Fig. 4, this includes the use of appropriate satellite instruments, calibration aspects (Level 0-1 processing), (Level 1-2) retrieval algorithms and data processing, validation of the satellite-derived data products and user assessments via different approaches (e.g., inverse modeling of regional surface fluxes, CCDAS (Carbon Cycle Data Assimilation System)).

Two types of retrieval algorithms are used within GHG-CCI: The so-called "ECV Core Algorithms" (ECAs) and the "Additional Constraints Algorithms" (ACAs). The ECAs are algorithms to retrieve XCO_2 and XCH_4 from the two core sensors SCIAMACHY/ENVISAT and TANSO/GOSAT. The ACAs are algorithms applied to sensors which provide information on CO_2 and CH_4 in "upper layers", i.e., atmospheric layers above the planetary boundary layer. This includes mid/upper tropospheric columns from AIRS and IASI and (primarily) stratospheric vertical profiles from SCIAMACHY solar occultation (CH_4, CO_2), MIPAS (CH_4) and ACE-FTS (CO_2).

GHG-CCI covers all aspects shown in Fig. 4 but the focus is on ECAs primarily in terms of (i) algorithm improvements (several algorithms per product are being developed in competition), (ii) data processing to generate global multi-year data set and (iii) evaluation of the generated data products in order to determine their quality. These ECA related aspects are also the focus of this manuscript.

Level 1 data are input data for CCI. Nevertheless (primarily SCIAMACHY) Level 0-1 processing experts are part of the GHG-CCI team in order to provide expertise and to make sure that feedbacks will result in future Level 1 data product improvements in case this turns out to be necessary. For GOSAT Level 1 and 2 data access, expertise and feedbacks, close links have been established with the GOSAT teams at JAXA and NIES.

The ground-based validation of the satellite-derived XCO_2 and XCH_4 data products largely relies on the Total Carbon Column Observing Network (TCCON) [24] as this network has been designed and developed for this purpose. In parallel, activities are ongoing to also use data from other sources in the future (NDACC, GAW, AGAGE). The validation is carried out by an independent validation team.

A dedicated GHG-CCI Climate Research Group (CRG) has been set up to represent the users of the satellite-derived CO_2 and CH_4 data products and to provide expertise on inverse modeling and other user related aspects. A strong link exists between GHG-CCI and the EU FP7 GMES project MACC (Monitoring of Atmospheric Composition and Climate, currently MACC-II). Several GHG-CCI team members are MACC members. GHG-CCI data products are delivered to MACC and MACC provides feedback on their usefulness.

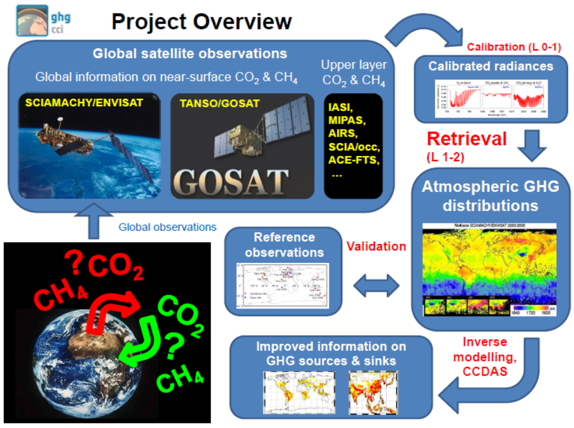

Fig. 4: GHG-CCI project overview.

The CCI project team is shown in Fig. 5. The team structure is essentially the same for all (currently) 13 CCI ECV projects.

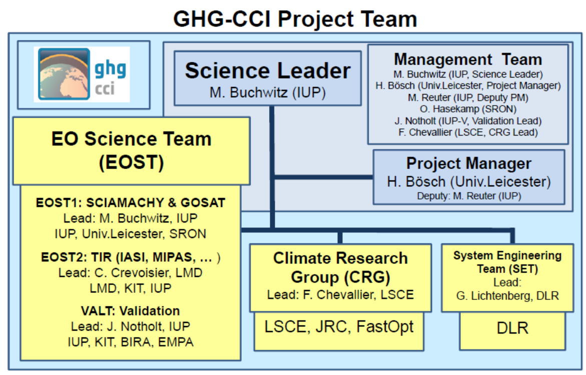

Fig. 5: GHG-CCI project team.

An overview about the GHG-CCI schedule is shown in Fig. 6. As can be seen, the project consists of four major phases: During the first 2 years the so called Round Robin (RR) exercise takes place (Sect. 3.2). The goal of the RR is to decide which algorithms to use to generate the Climate Research Data Package (CRDP), i.e., the first ECV GHG data base. After RR, the CRDP will be generated, validated and assessed by users. All results will be documented in dedicated reports (denoted PVIR and CAR in Fig. 6).

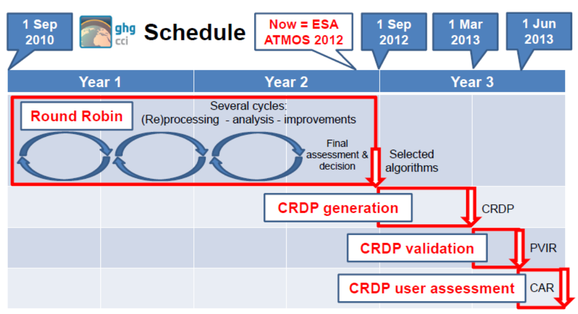

Fig. 6: GHG-CCI project schedule. The main goal is to generate the Climate Research Data Package (CRDP).

3. GHG-CCI PROJECT STATUS

3.1 User requirements

One of the first key activities carried out in this project was the establishment of the user requirements. They have been formulated in the GHG-CCI User Requirements Document (URD) [2]. Table 1 lists the requirements for random and systematic errors ("precision and accuracy").

The most challenging requirement is the relative accuracy requirement for XCO_2. The threshold requirement is 0.5 ppm because even errors of a few tenth of a ppm can result in quite large errors of the inferred CO_2 surface fluxes when used as input data for inverse modeling schemes [2]. However, to what extent systematic errors result in biases of the inferred fluxes, depends on the spatio-temporal pattern of the systematic errors. A global bias, even if considerably larger than the required 0.5 ppm, would not be critical at all. Most critical are systematic errors which result in regional (~1000 km) biases on an approximately monthly time scale. This means that even if the listed single numerical value is not met (on average), this does not mean that the data are useless. On the other hand, depending on the error structure, even if the requirement is met (on average), this does not mean that the data are definitely particularly useful in all cases. It all depends on the spatio-temporal pattern of the errors. The requirements reflect what the GHG-CCI users would like to see achieved. The threshold (i.e., minimum) requirements should not be interpreted in the sense "worse is useless" but in the sense "minimum wanted or needed". To what extent the data are useful can ultimately only be determined by a careful analysis of the existing data products rather than by computing single numbers to be compared with the corresponding values as listed in Tab. 1. The numbers listed in Tab. 1 should therefore not be over-interpreted.

Requirements for regional CO_2 and CH_4 source/sink determination using SCIAMACHY/ENVISAT and TANSO/GOSAT					
Parameter	**Req. type**	**Random error** ("Precision")		**Systematic error** ("Accuracy")	**Stability**
		Single obs.	1000^2 km², monthly		
XCO_2	G	< 1 ppm	< 0.3 ppm	< 0.2 ppm (absolute)	As systematic error but per year
	B	< 3 ppm	< 1.0 ppm	< 0.3 ppm (relative $^{§)}$)	-"-
	T	< 8 ppm	< 1.3 ppm	< 0.5 ppm (relative $^{\#)}$)	-"-
XCH_4	G	< 9 ppb	< 3 ppb	< 1 ppb (absolute)	As systematic error but per year
	B	< 17 ppb	< 5 ppb	< 5 ppb (relative $^{§)}$)	-"-
	T	< 34 ppb	< 11 ppb	< 10 ppb (relative $^{\#)}$)	-"-

Table 1: GHG-CCI XCO_2 and XCH_4 random ("precision") and systematic ("accuracy") uncertainty requirements for measurements over land. Abbreviations: G=Goal, B=Breakthrough, T=Threshold requirement. $^{§)}$ Required systematic error after bias correction, where only the application of a constant offset / scaling factor independent of time and location is permitted for bias correction. $^{\#)}$ Required systematic error after bias correction, where bias correction is not limited to the application of a constant offset / scaling factor. From [2].

3.2 Round Robin (RR) related activities

Several algorithms - ECAs (Tab. 2) and ACAs (Tab. 5) - have been further developed and assessed during GHG-CCI. Table 3 presents and overview about the achieved XCO_2 data quality as obtained after the first year of the GHG-CCI project (end of Aug. 2011). As can be seen, not all requirements had been met, especially not the challenging XCO_2 relative accuracy requirement. Table 4 shows the corresponding results for XCH_4.

Using improved algorithms, all data have been re-processed during the second year of the project. The analysis of these new data sets is currently ongoing. The final RR decision will be made following the RR evaluation criteria as described in [11] (Fig. 7). This decision will be available end of Aug. 2012. In the following Sect. 4 more details are given on the SCIAMACHY and GOSAT XCO_2 data products.

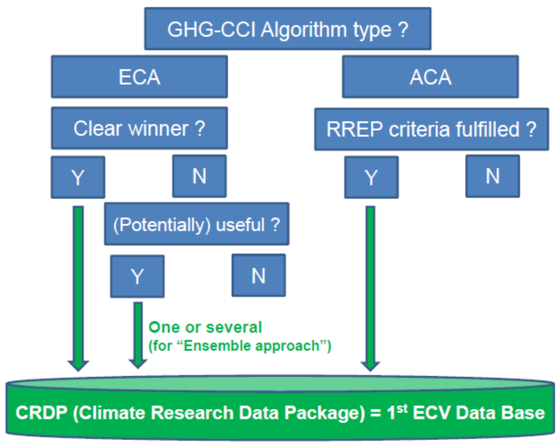

Fig. 7: Overview GHG-CCI RR algorithm selection procedure. For details see RR Evaluation Protocol [11].

GHG-CCI ECV Core Algorithms (ECAs)				
Algorithm ID	**Data product**	**Sensor**	**Algorithm**	**References**
CO2_SCI_BESD	XCO_2	SCIAMACHY	BESD	*Reuter et al. [19,20]*
CO2_SCI_WFMD	XCO_2	SCIAMACHY	WFM-DOAS	*Schneising et al. [21,22]*
CO2_GOS_OCFP	XCO_2	TANSO/GOSAT	UoL OCO FP	*Parker et al. [17]*
CO2_GOS_SRFP	XCO_2	TANSO/GOSAT	SRON/KIT FP ("RemoteC")	*Butz et al. [3]*
CH4_SCI_WFMD	XCH_4	SCIAMACHY	WFM-DOAS	*Schneising et al. [21,22]*
CH4_SCI_IMAP	XCH_4	SCIAMACHY	IMAP	*Frankenberg et al. [8]*
CH4_GOS_OCFP	XCH_4	TANSO/GOSAT	UoL OCO FP	*Parker et al. [17]*
CH4_GOS_OCPR	XCH_4	TANSO/GOSAT	UoL PR	*Parker et al. [17]*
CH4_GOS_SRFP	XCH_4	TANSO/GOSAT	SRON/KIT FP	*Butz et al. [3]*
CH4_GOS_SRPR	XCH_4	TANSO/GOSAT	SRON/KIT PR	*Butz et al. [3]*

Table 2: Overview GHG-CCI ECV Core Algorithms (ECAs). Abbrevations: UoL: Univ. of Leicester, OCO: Orbiting Carbon Observatory, FP: "Full Physics" algorithm, PR: Light path "PRoxy" algorithm.

Estimates of achieved data quality (status August 2011): XCO_2 (in ppm)					
Sensor	**Algorithm**	**Precision** Single observation	**Precision** Regional / monthly	**Relative accuracy**	**Method**
SCIAMACHY	BESD v00.08.20 (CO2_SCI_BESD)	2.5 < 2.3	NA 2.0	0.8 0.8	DP (IUP) RR
SCIAMACHY	WFMD v2.1 (CO2_SCI_BESD)	5.4 < 9.1	2.2 2.6	1.2 1.9	DP (IUP) RR
GOSAT	OCFP v2 (CO2_GOS_OCFP)	2.0 < 2.3	0.23 1.3	1.0 0.9	DP (UoL) RR
GOSAT	SRFP v1.0 (CO2_GOS_SRFP)	2.7 < 2.6	NA 0.9	1.0 0.9	DP (SRON/KIT) RR
Required according to URD [2]:		< 8.0	< 1.3	< 0.5	

Table 3: Overview GHG-CCI estimated data quality for satellite-derived XCO_2 as determined at the end of the first year of the GHG-CCI project based on comparisons with TCCON. Green indicates that the corresponding requirement (see bottom row) likely has been met (note: the numbers largely stem from comparisons at a limited number of ground stations). Abbreviation: NA: "Not Assessed", DP: Data Provider assessment method (as used by data provider listed in brackets), RR: Round Robin assessment method. See [10] for details. From [10].

Estimates of achieved data quality (status August 2011): XCH_4 (in ppb)					
Sensor	**Algorithm**	**Precision** Single observation	**Precision** Regional / monthly	**Relative accuracy**	**Method**
SCIAMACHY	WFMD v2.0 (CH4_SCI_WFMD)	P1: 2003-2005: 30 P2: 2006-2009: 70 P1: 2003-2005: < 35 P2: 2006-2009: < 83	P1: 12 P2: 13-16 P1: 8 P2: 19	P1: 3 P2: 16-24 P1: NA P2: 30	DP (IUP) RR
SCIAMACHY	IMAP v5.5 (CH4_SCI_IMAP)	15-35 P1: 2003-2005: < 35 P2: 2006-2009: < 48	15 P1: 10 P2: 14	15 P1: NA P2: 15	DP (SRON/JPL) RR
GOSAT	OCFP v2.0 (CH4_GOS_OCFP)	7-13 < 12	1 9	9 (*)	DP (UoL) RR
GOSAT	SRPR v1.0 (CH4_GOS_SRFP)	16 < 15	NA 6	~4 4	DP (SRON/KIT) RR
GOSAT	SRFP v1.0 (CH4_GOS_SRPR)	15 < 14	NA 6	~5 4	DP (SRON/KIT) RR
Required according to URD [2]:		< 34	< 11	< 10	

Table 4: As Tab. 3 but for XCH_4. Note that for SCIAMACHY the assessment is made for two time periods (P1: 2005 and earlier; P2: 2006 and later) to consider the detector degradation after 2005. (*) Value (19 ppb) removed due to bias problems with the Bialystok TCCON data. From [10].

GHG-CCI Additional Constraints Algorithms (ACAs)				
Algorithm ID	**Data product**	**Sensor**	**Algorithm**	**References**
CO2_AIR_NLIS	Mid/upper tropospheric column	AIRS	NLIS	*Crevoisier et al. [4]*
CO2_IAS_NLIS	Mid/upper tropospheric column	IASI	NLIS	*Crevoisier et al. [5]*
CO2_ACE_CLRS	Upper trop. / stratospheric profile	ACE-FTS	CLRS	*Foucher et al. [7]*
CO2_SCI_ONPD	Stratospheric profile	SCIAMACHY	ONPD	*(Noël et al [14])* (*)
CH4_IAS_NLIS	Upper trop. / stratospheric profile	IASI	NLIS	*Crevoisier et al. [6]*
CH4_MIP_IMK	Upper trop. / stratospheric profile	MIPAS	KIT/IMK MIPAS	*von Clarmann [23]*
CH4_SCI_ONPD	Stratospheric profile	SCIAMACHY	ONPD	*Noël et al [14]*

Table 5: Overview GHG-CCI Additional Constraints Algorithms (ACAs). (*)Note that CO2_SCI_ONPD is a new algorithm "similar" as the one described in Noël et al [14], which has been added in the 2nd year of GHG-CCI.

4. XCO_2: ENSEMBLE MEDIAN ALGORITHM (EMMA)

Preliminary analysis of the various satellite XCO_2 data products shows that (i) the differences between the data sets generated with different algorithms are often larger than the required relative accuracy (Figs. 8 and 9), (ii) the TCCON validation network [24] is too sparse to cover all geo-physically relevant conditions and to clearly identify which algorithm is the best and (iii) each algorithm has its strength and weaknesses. The situation appears to be similar as for climate modeling: it is not clear which "model" is the best and (remote from TCCON) there is no truth to compare with. A promising approach to deal with this is to make use of the fact that several state-of-the-art algorithms and corresponding XCO_2 data products are available, i.e., an ensemble of data products, which can be used. This is the underlying idea of the EnseMble Median Algorithm (EMMA). The present version of EMMA (v1.2d) uses 7 satellite XCO_2 products (see Figs. 8 and 9) and generates a Level 2 product using the median in each 10^ox10^o monthly grid cell. Ongoing analysis indicates that the EMMA product outperforms each individual product. EMMA also enables to estimate realistic uncertainties obtained from the inter-algorithm scatter. It is planned to add the EMMA product to the GHG-CCI product portfolio.

5. OUTLOOK

Currently, CCI is in Phase 1 (~2011-2013) but a Phase 2 is foreseen for ~2014-2016. Which GHG-CCI data products are expected to be available when and what time period they (likely) cover is indicated in Tab. 6. Note that the final Phase 2 plan will likely not be available before end of 2013.

GHG-CCI products and their availability															
Product ID	**Product** (Level 2, mixing ratios)	**Years processed**													
		2003	**04**	**05**	**06**	**07**	**08**	**09**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
ECV Core Products (ECAs)															
XCO2_SCIA	**XCO_2**														
XCH4_SCIA	**XCH_4**														
XCO2_GOSAT	**XCO_2**														
XCH4_GOSAT	**XCH_4**														
XCH4_S5P	**XCH_4**														
XCO2_OCO2	**XCO_2**														
Additional Constraints Products (ACAs)															
CO2_AIRS	**CO_2 (1)**														
CO2_IASI	**CO_2 (1)**														
CH4_IASI	**CH_4 (1)**														
CH4_SCIAOCC	**CH_4 (2)**														
CO2_SCIAOCC	**CO_2 (2)**														
CH4_MIPAS	**CH_4 (2)**														
CO2_ACEFTS	**CO_2 (2)**														

Color code:		
CCI Phase 1:	**CCI Phase 2 (preliminary):**	
		(*)

(1) Mid / upper tropospheric column; (2) Upper tropospheric / stratospheric profile; (*)/grey: Possibly limitations (e.g., only if mission available, only preparatory activities, depending on funding, etc.); Note: Likely need for re-processing of "Phase 1 years" (green) during Phase 2 to ensure consistent time series.

Table 6: Overview GHG-CCI product availability. Green shows the data products and their time coverage generated during Phase 1 of CCI (2011-2013). Blue and grey indicates the products which may be generated during Phase 2 of CCI (2014-2016). Abbreviations: S5P: Sentinel-5-Precursor, OCO-2: Observing Carbon Observatory 2.

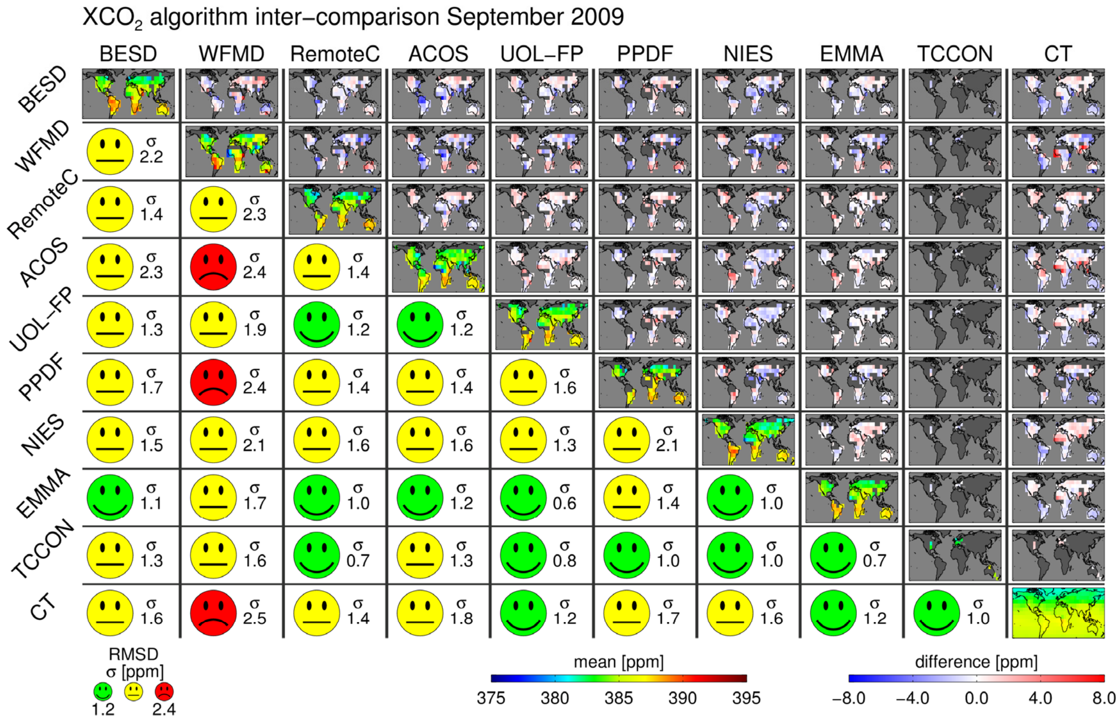

Fig. 8: Comparison of various XCO_2 data products for September 2009. From left to right: Satellite: CO2_SCI_BESD [19,20], CO2_SCI_WFMD [21,22], CO2_GOS_SRFP (= RemoteC) [3], NASA/ACOS [15], CO2_GOS_OCFP (=UoL-FP) [17], PPDF [16], NIES (= GOSAT operational algorithm) [25], EMMA (version 1.2d). Ground-based: TCCON [24]. Model: NOAA's CarbonTracker (CT) [18]. On the diagonal 10^ox10^o global XCO_2 maps are shown obtained by averaging the individual XCO_2 data products. The off-diagonal elements show the differences between the XCO_2 maps (above diagonal) and the 1-sigma standard deviation between the differences (below diagonal). The smileys are shown in green if the standard deviation of the difference is less than 1.2 ppm, in red if the differences are larger than 2.4 ppm and yellow otherwise.

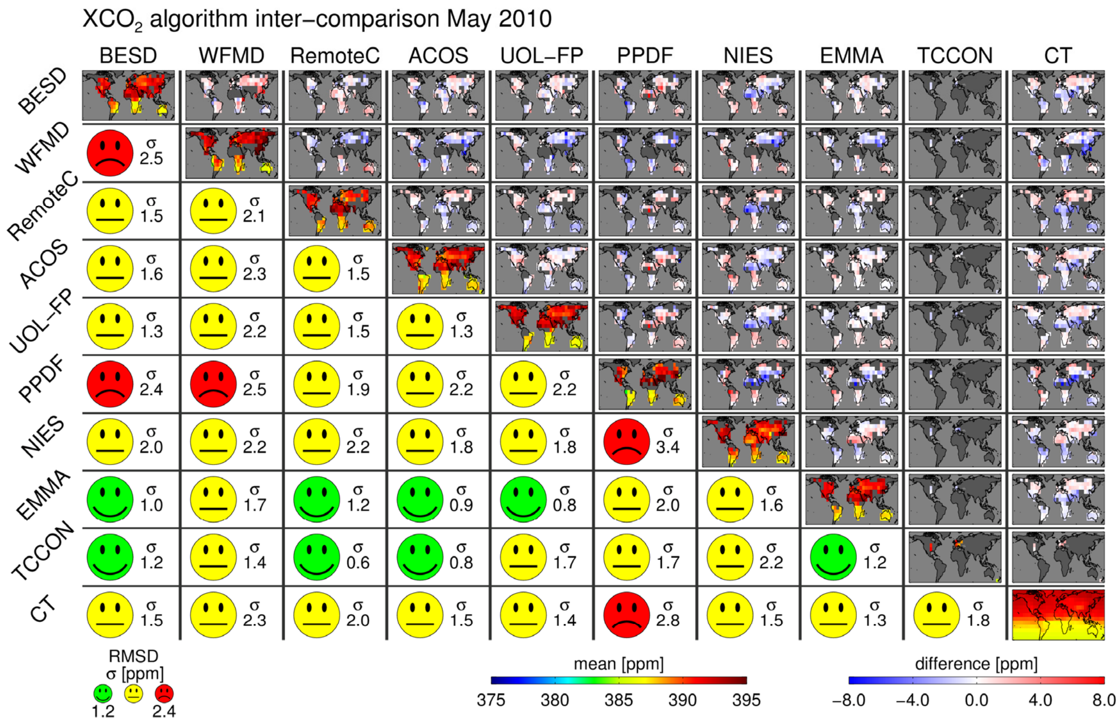

Fig. 9: As Fig. 8 but for May 2010.

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