THE GREENHOUSE GAS PROJECT OF ESA'S CLIMATE CHANGE INITIATIVE (GHG-CCI): PHASE 1 ACHIEVEMENTS

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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 delivers data sets of various Essential Climate Variables (ECVs). The goal of GHG-CCI is to generate global satellite-derived data sets of the two important anthropogenic greenhouse gases (GHG) carbon dioxide (CO_2) and methane (CH_4) with a quality as needed 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 Phase 1 of the GHG-CCI project (Sept.2010 – Dec.2013), focusing on scientific achievements and on the "Climate Research Data Package" (CRDP), which is the first version of the ECV GHG data base.

1. INTRODUCTION

Carbon dioxide (CO_2) is the most important anthropogenic greenhouse gas causing global warming [29]. Despite its importance, our knowledge of CO_2 sources and sinks has significant gaps [10,12,22,23], 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 [29]. This is also true for methane (CH_4) [2,3,18,29,42]. The goal of the GHG-CCI project, which is one of several projects of ESA's Climate Change Initiative (CCI, [28]), is to generate global satellite-derived CO_2 and CH_4 data sets as needed to improve our understanding of the sources and sinks of these important gases.

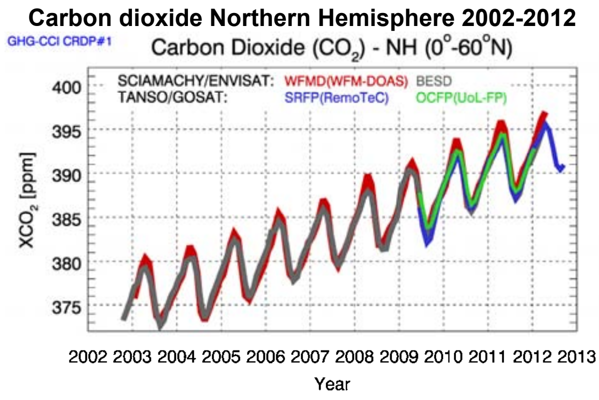

Fig. 1: Time evolution of Northern Hemispheric XCO_2, i.e., of the column-averaged CO_2 mixing ratio, as retrieved from SCIAMACHY/ENVISAT and TANSO-FTS/GOSAT using four different GHG-CCI retrieval algorithms (see Sect. 4). Clearly visible is the CO_2 seasonal cycle - primarily caused by uptake and release of CO_2 by the terrestrial biosphere - and the atmospheric CO_2 increase with time, which is primarily caused by burning of fossil fuels. Also visible is the good agreement of the different CO_2 data products. Perfect agreement is not expected due to different spatio-temporal sampling and different altitude sensitivities (averaging kernels).

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Global near-surface sensitive satellite observations of CO_2 and CH_4 combined with modeling permits to obtain information on regional sources and sinks. The goal of the GHG-CCI project is to generate the Essential Climate Variable (ECV) Greenhouse Gases (GHG) as required by GCOS [22,23]. The GCOS definition of this ECV is [22]:

- "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 only data 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) [5] and TANSO-FTS on-board GOSAT (launched in 2009) [30]. Both instruments perform (or have performed until recently) 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, i.e., XCO_2 (in ppm) and XCH_4 (in ppb)). These two instruments are therefore 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) 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 (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. 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 User Requirements Document (URD) [8], which is available from the GHG-CCI website (http://www.esa-ghg-cci.org -> Documents)

Another focus was to improve existing retrieval algorithms in order to generate data products which meet the challenging user requirements. Several algorithms per data product have been further developed and iteratively improved in competition. This activity was referred to as "Round Robin" (RR) exercise within the CCI. For GHG-CCI the RR phase covered the first two years of this project (Sep. 2010 – Aug. 2012). The GHG-CCI RR approach and results are presented in detail in *Buchwitz et al., 2013a* [7] (a link to that paper is given on the GHG-CCI website: http://www.esa-ghg-cci.org -> Publications).

The selected algorithms have been used to generate the "Climate Research Data Package" (CRDP), which is the first version of the ECV GHG data base. The discussion of the CRDP is the focus of this manuscript.

This manuscript is structured as follows: In Sect. 2 a short overview about the GHG-CCI Round Robin exercise is given, which was a key activity during Phase 1. Sect. 3 provides an overview about the scientific achievements of the GHG-CCI project as achieved until now. In Sect. 4 the CRDP is presented. Finally, an outlook is given in Sect. 5.

2. ROUND ROBIN (RR) EXERCISE

A detailed discussion of the GHG-CCI Round Robin (RR) approach and results obtained is given in *Buchwitz et al., 2013a* [7]. As shown in [7], significant progress has been made in terms of improving the precision and accuracy of the various GHG-CCI data products (see also Sect. 4). Several user requirements have been met, but not all. For example, satellite XCO_2 comparisons with ground-based TCCON retrievals [52] indicate that typically a relative accuracy of 1 ppm has been achieved but not the required 0.5 ppm. Furthermore, it has been identified that remote from (the sparse) TCCON validation sites also differences larger than 1 ppm have been found when comparing the various global XCO_2 data products from SCIAMACHY and GOSAT (e.g., over parts of the tropics, where no validation sites exist) [7, 37]. This aspect needs further investigation but it appears that all products suffer from outliers at least to some extent.

A tool to assess the quality of the global satellite retrievals without having a reliable standard to compare with is the developed EMMA approach [37]. EMMA stands for "EnseMble Median Algorithm". Via EMMA a new Level 2 XCO_2 product is being generated by selecting the median of all available individual products (within pre-defined spatio-temporal intervals). The EMMA product has been used as a reference for comparison with the individual products and several statistical quantities have been computed for each product such as "percentage of observations in agreement with the median" and "percent outliers". It has also been agreed to add the EMMA product to the GHG-CCI data products portfolio and to assess the quality of the merged SCIAMACHY and GOSAT XCO_2 product via inverse modeling of CO_2 surface fluxes. The EMMA product has therefore been added to the CRDP (see Sect. 4).

The goal of the RR exercise was to identify which algorithms to use to generate the CRDP. As shown in [7], it was not possible for all products to identify a single algorithm. For products where this was not possible, significant differences have been identified, but it was not possible to clearly identify, which algorithm/product is the more accurate. For these products several algorithms (typically two) have been selected for further development and analysis of the resulting data products.

Before the CRDP is presented in Sect. 4, we shortly summarize key scientific achievements as obtained during Phase 1 of the GHG-CCI project.

3. OVERVIEW GHG-CCI PHASE 1 SCIENTIFIC ACHIEVEMENTS

In this section an overview is provided on scientific publications, which have been published during GHG-CCI Phase 1 using GHG-CCI data products. The list of all publications is also available via the GHG-CCI website (http://www.esa-ghg-cci.org -> Publications), where also links to all publications are given. Please visit that website for the most up-to-date list of all publications.

Several publications are addressing improvements of the retrieval algorithms, e.g.,

- *Reuter et al., 2011* [40], presents first results from the application of the advanced BESD algorithm [41] to SCIAMACHY XCO_2 retrieval. BESD has been developed to improve the accuracy and precision compared to the simpler but much faster WFMD algorithm and as shown in [7], this goal has been achieved.
- However, the WFMD algorithm has also been significantly improved during GHG-CCI Phase 1 as shown in *Heymann et al., 2012a, 2012b* [26,27] and *Schneising et al., 2011, 2012, 2013a/b* [45,46,47,48] and used to address important science issues [45,46,47,48] as described below.
- GOSAT algorithm improvements are reported in a number of publications: *Butz et al., 2011* [9], *Cogan et al., 2012* [13], *Guerlet et al., 2013a, 2013b* [24,25], *Parker et al., 2011* [35], *Schepers et al., 2012* [44].

In a number of papers results for various carbon related applications are presented. In the following papers, the GHG-CCI algorithms / data products have been used to enhance our knowledge on CO_2 and CH_4 sources and sinks:

- *Schneising et al., 2011* [48] 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 assimilation system CarbonTracker [36]. 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.
- *Schneising et al., 2013b* [45] 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 very good agreement with CarbonTracker.
- *Schneising et al., 2013a* [46] presents 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 CO_2 enhancements and trends with the emission inventory EDGAR. They found no significant trend for the Rhine-Ruhr area in central Europe and the US East Coast but a significant increasing trend for the Yangtze River Delta in China of about 13+/-8%/year, in agreement with EDGAR (10+/-1%/year).
- *Reuter et al., 2013* [37] computed CO_2 seasonal cycle amplitudes using various satellite XCO_2 data products (GHG-CCI products but also the GOSAT XCO_2 products generated in Japan at NIES [34,53] and the NASA ACOS product [33]) and compared the amplitudes with TCCON and CarbonTracker. They found that most of the satellite products agree with TCCON but 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 [7] for a discussion of these findings).
- *Guerlet et al., 2013b* [24] 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.
- *Ross et al., 2013* [43] used GOSAT data to obtain information on wildfire emissions. Using global GOSAT XCO_2 data, *Basu et al., 2013* [1] presents 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 suggest that Europe is a stronger carbon sink than expected.
- A number of publications have focused on the unexpected renewed atmospheric methane increase during 2007 and later years [2,15,20,48,50]. 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 [48] but a particular region responsible for the increase has not been identified [20,48]. Using inverse modeling and SCIAMACHY retrievals and NOAA surface data for 2003-2010 it has been recently [2] identified 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 emissions have also been obtained from GOSAT. Whereas the SCIAMACHY data have already been used to improve our knowledge on regional methane emissions prior to the start of the GHG-CCI project (e.g., [3] using the SCIAMACHY data described in [20]), first results from GOSAT have now also been obtained as presented in *Cressot et al., 2013* [14] and *Fraser et al., 2013* [21].

Note that publications addressing various other aspects have also been published, e.g., validation aspects (*Sussmann et al., 2011, 2013* [49,51]) or aspects important for the users of the atmospheric data products, e.g., error statistics as discussed in *Chevallier et al., 2013* [11]. *Reuter et al., 2012a* [38] has used the BESD algorithm to assess to what extent information on CO_2 isotopologues can be retrieved from GOSAT. In *Reuter et al., 2012b* [39] an empirical CO_2 model is presented and several applications of this are discussed, e.g., its use as *a priori* information for retrieval algorithms.

For ACAs, also a number of publications have been published, e.g.,

- *Crevoisier et al., 2013* [15] presents several years (2007-2011) of MetOp-A/IASI mid/upper tropospheric methane in the tropics. They focus on identifying the reason for the recent methane increase starting in 2007. They found that the largest increase is during 2007-2008 with only a slight increase during 2009-2011 probably due to decreasing tropical wetland emissions during the later years.
- *Noël et al., 2011* [32], present for the first time a long time series (2003-2010) of stratospheric methane vertical profiles retrieved from SCIAMACHY solar occultation measurements at mid to high latitudes over the Northern Hemisphere.
- *Laeng et al., 2013* [31] presents the validation of methane vertical profiles retrieved from MIPAS including comparisons with the SCIAMACHY product described in [32].
- The algorithm for the CO_2 product from ACE-FTS is described in [19].

GHG-CCI team members are also involved in the specification of future GHG satellites such as CarbonSat [4,6]. In this context see also *Ciais et al., 2013* [12] for an overview about current capabilities and limitations and future needs for establishing a global carbon observing system.

4. CLIMATE RESEARCH DATA PACKAGE (CRDP)

In this section, we present an overview about the GHG-CCI CRDP, which is the first version of the GHG-CCI ECV GHG products data base. The CRDP consists of various satellite-derived CO_2 and CH_4 data products and related documentation. The satellite-derived data products have been generated and are stored in a data bases accessible via ftp (http://www.esa-ghg-cci.org -> CRDP). Currently ongoing activities are the validation of the CRDP and an initial user assessment. The validation results will be reported in a document called "Product Validation and Intercomparison Report" (PVIR) and the user assessments will be reported in the "Climate Assessment Report" (CAR). Both documents, PVIR and CAR, are planned to be ready in October 2013 and will be made publicly available along with the satellite data products via the GHG-CCI website.

An overview about the various satellite-derived data products stored in the CRDP data base is given in Tabs. 1 and 2. Table 1 lists the GHG-CCI ECV core data products, which are the column-averaged mixing ratios of CO_2, denoted XCO_2 (in ppm), and CH_4, denoted XCH_4 (in ppb), as retrieved from SCIAMACHY and TANSO-FTS/GOSAT using European retrieval algorithms. Table 2 lists the "Additional Constraints" data products providing information on CO_2 and CH_4 in atmospheric layers above the planetary boundary layer. To illustrate how the various data products "look like", the CRDP website provides various images (maps and time series) and related information. Some figures are presented and discussed in the following sub-sections.

4.1 CRDP XCO_2 PRODUCTS

Figure 2 shows global XCO_2 maps and time series as retrieved from SCIAMACHY. Due to the low reflectivity of water in the short-wave-infrared spectral region used for CO_2 retrieval, only data over land are shown. Data gaps over land are primarily due to clouds but also because of too low solar zenith angles (esp. in winter) and snow and ice covered surface. Clearly visible in the time series (red curve), but also in the seasonal maps, is the CO_2 seasonal cycle with low CO_2 values in summer due to uptake of CO_2 by the growing vegetation. Figure 3 shows one of the two GHG-CCI XCO_2 products from GOSAT.

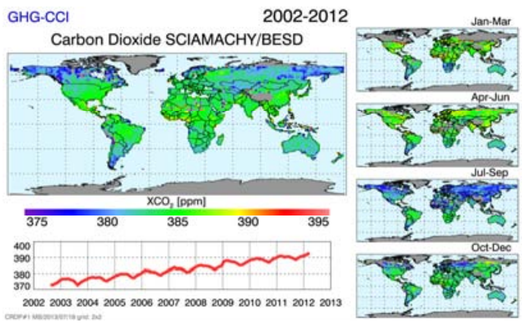

Fig. 2: Overview SCIAMACHY/BESD XCO_2 data product [40] for 2002-2012.

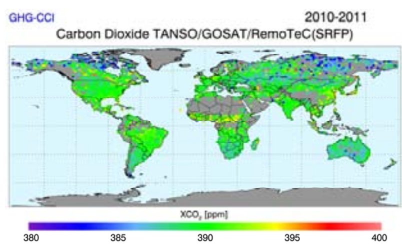

Fig. 3: Similar as Fig. 2 but for XCO_2 retrieved from GOSAT [24,25].

GHG-CCI CRDP: ECA Products				
Algorithm / Product ID	**Product**	**Sensor**	**Algorithm Institute**	**Comment Temporal coverage**
CO2_SCI_BESD v02.00.04	XCO_2	SCIAMACHY	BESD [40] IUP	*RR: Selected for SCIA XCO_2; Coverage:08.2002-03.2012*
CO2_SCI_WFMD v3.3	XCO_2	SCIAMACHY	WFM-DOAS [45] IUP	*More data than BESD; used for EMMA XCO_2; Coverage:01.2003-04.2012*
CO2_GOS_OCFP v4.0	XCO_2	TANSO	UoL-FP [13] UoL	*RR: Not clear if better or worse than SRFP; Coverage:06.2009-01.2012*
CO2_GOS_SRFP v2.1	XCO_2	TANSO	RemoteC [24] SRON/KIT	*RR: Not clear if better or worse than OCFP; Coverage:06.2009-09.2012*
CO2_EMMA v1.5	XCO_2	SCIA & TANSO	EMMA [37] Lead: IUP	*Merged ensemble product; Coverage:06.2009-07.2010*
CH4_SCI_WFMD v3.3	XCH_4	SCIAMACHY	WFM-DOAS [45-48] IUP	*RR: Not clear if better or worse than IMAP; Coverage:08.2002-12.2011*
CH4_SCI_IMAP v6.0	XCH_4	SCIAMACHY	IMAP [20] SRON/JPL	*RR: Not clear if better or worse than WFMD; Coverage:01.2003-04.2012*
CH4_GOS_OCPR v4.0	XCH_4	TANSO	UoL-PR [35] UoL	*RR: Selected for GOSAT PRoxy (PR) XCH_4; Coverage:06.2009-12.2011*
CH4_GOS_SRFP v2.1	XCH_4	TANSO	RemoteC [9] SRON/KIT	*RR: Selected for GOSAT Full Physics (FP) XCH_4; Coverage:06.2009-09.2012*

Table 1: Overview GHG-CCI Phase 1 CRDP "ECV Core Algorithm" (ECA) data products.

GHG-CCI CRDP: ACA Products				
Algorithm / Product ID	**Product**	**Sensor**	**Algorithm Institute**	**Temporal coverage**
CO2_AIR_NLIS	Mid/upper tropospheric column	AIRS	NLIS [17] / LMD	*2003-2007*
CO2_IAS_NLIS	Mid/upper tropospheric column	IASI	NLIS [16] / LMD	*2007-2011*
CO2_SCI_ONPD	Stratospheric profile	SCIA	ONPD [32] / IUP	*2002-2012*
CO2_ACE_CLRS	Upper trop. / stratospheric profile	ACE-FTS	CLRS [19] / LMD	*2004-2010*
CH4_IAS_NLIS	Upper trop. / stratospheric profile	IASI	NLIS [15] / LMD	*2007-2011*
CH4_MIP_IMK	Upper trop. / stratospheric profile	MIPAS	MIPAS [31] / KIT-IMK	*2005-2011*
CH4_SCI_ONPD	Stratospheric profile	SCIA	ONPD [32] / IUP	*2002-2012*

Table 2: Overview GHG-CCI Phase 1 CRDP "Additional Constraints Algorithm" (ACA) data products.

The CRDP website also shows "browse images" for every month for all products listed in Tab. 1. Shown are the main product, e.g., XCO_2, but also the number of observations per 10^ox10^o grid cell, the mean value of the reported uncertainty, and the standard deviation. Figures 4 and 5 show two example figures for XCO_2.

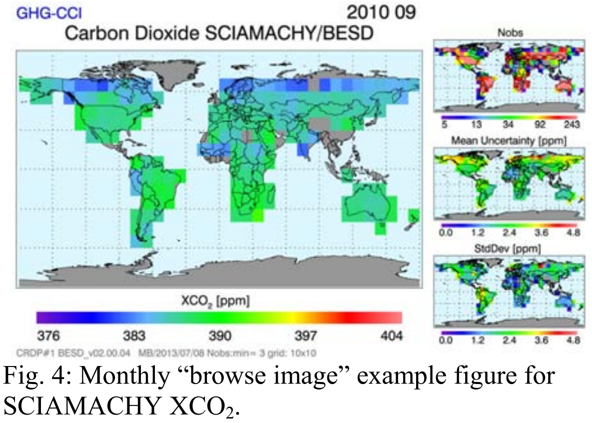

Fig. 4: Monthly "browse image" example figure for SCIAMACHY XCO_2.

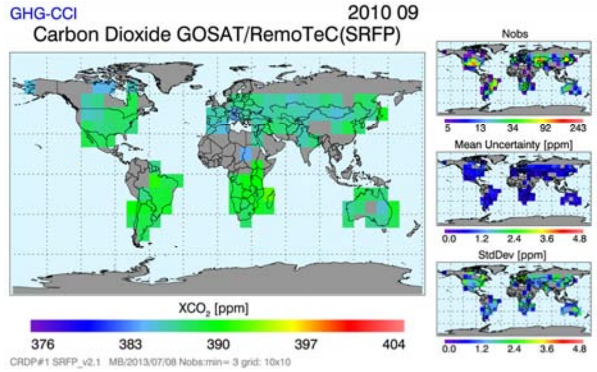

Fig. 5: Monthly "browse image" example figure for GOSAT XCO_2.

4.2 CRDP XCH_4 PRODUCTS

Figures 6-10 are similar as Figs. 1-5 but show satellite-derived column-averaged methane retrievals. Note that the SCIAMACHY data after mid 2010 suffer from severe detector degradation (starting already end of 2005).

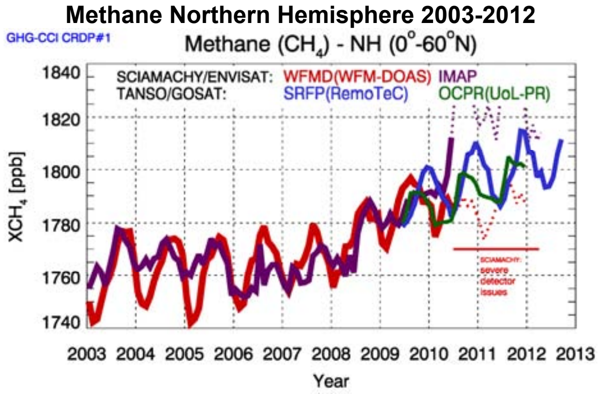

Fig. 6: Similar as Fig.1 but for methane.

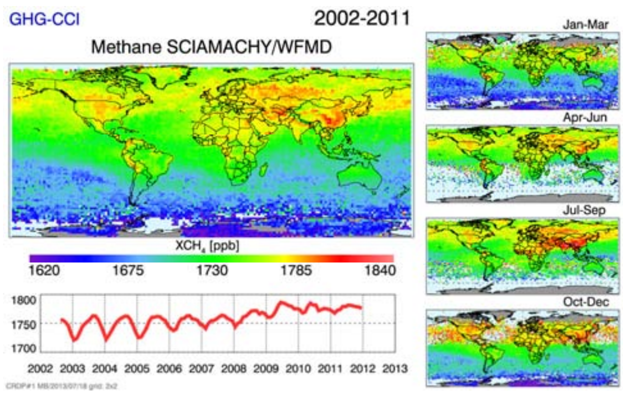

Fig. 7: Similar as Fig. 2 but for methane. Shown is the SCIAMACHY methane product retrieved with the WFMD algorithm [47,48].

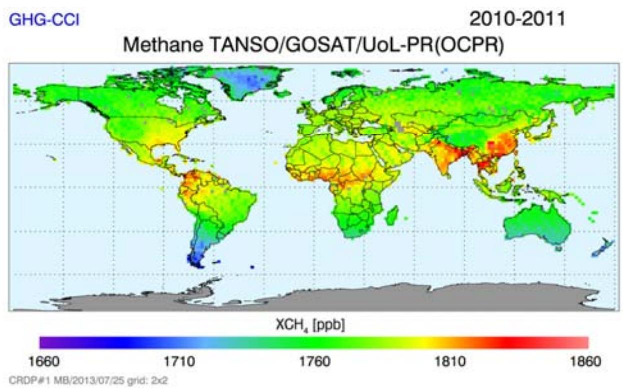

Fig. 8: Similar as Fig. 3 but for methane. Shown is the GOSAT methane product retrieved with the UoL-PR algorithm [35].

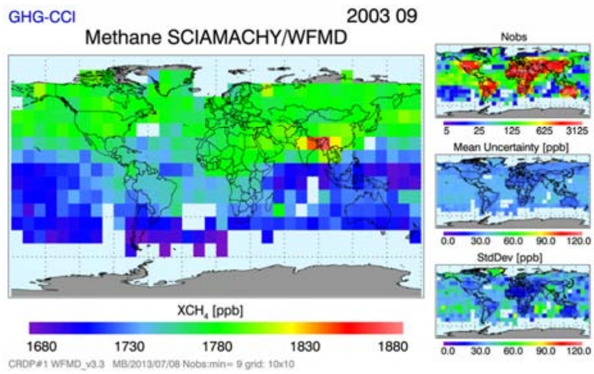

Fig. 9: Similar as Fig. 4 but for SCIAMACHY XCH_4.

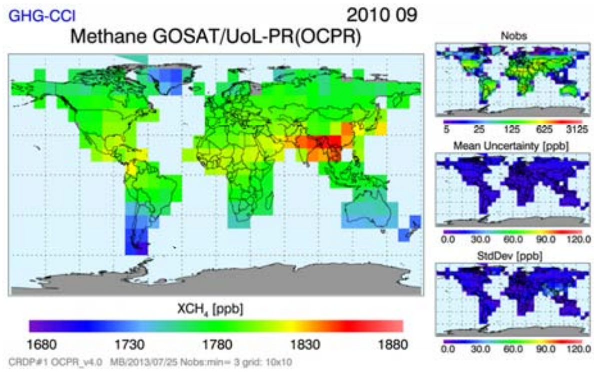

Fig. 10: Similar as Fig. 5 but for GOSAT XCH_4.

5. OUTLOOK

In this manuscript we have presented an overview about Phase 1 of the GHG-CCI project, which will end in December 2013. Phase 2 of this project is planned to start in January 2014 (2014-2016). During that phase focus will be on extension of the time series, on improving the existing ones (via three planned major re-processing cycles) and by also preparing for upcoming new missions such as OCO-2 and Sentinel-5-Precursor. It is also foreseen to involve more users in order to better exploit the information content of the satellite observations.

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