THE GHG-CCI PROJECT OF ESA'S CLIMATE CHANGE INITIATIVE: DATA PRODUCTS AND APPLICATION

M. Buchwitz [1], M. Reuter [1], O. Schneising [1], H. Boesch [2], I. Aben [3], M. Alexe [4], P. Bergamaschi [4], H. Bovensmann[1], D. Brunner [6], B. Buchmann [6], J. P. Burrows [1], A. Butz [7], F. Chevallier [8], C. D. Crevoisier [5], M. De Mazière [10], E. De Wachter [10], R. Detmers [3], B. Dils [10], L. Feng[9], C. Frankenberg [11], O. P. Hasekamp [3], W. Hewson[2], J. Heymann [1], S. Houweling [3], T. Kaminski [12], A. Laeng [7], T. T. v. Leeuwen [3], G. Lichtenberg [13], J. Marshall [14], S. Noël [1], J. Notholt [1], P. I. Palmer [9], R. Parker [2], A.-M. Sundström[6], M. Scholze [15], G. P. Stiller [7], T. Warneke [1], C. Zehner [16]

1. *Institute of Environmental Physics (IUP), University of Bremen, Bremen, Germany, E-mail: Michael.Buchwitz@iup.physik.uni-bremen.de*
2. *University of Leicester, Leicester, United Kingdom*
3. *SRON Netherlands Institute for Space Research, Utrecht, The Netherlands*
4. *European Commission Joint Research Centre (EC-JRC), Institute for Environment and Sustainability (IES), Air and Climate Unit, Ispra, Italy*
5. *Laboratoire de Météorologie Dynamique (LMD), Palaiseau, France*
6. *Swiss Federal Laboratories for Materials Science and Technology (Empa), Dübendorf, Switzerland*
7. *Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany*
8. *Laboratoire des Sciences du Climat et de l'Environnement (LSCE), Gif-sur-Yvette, France*
9. *University of Edinburgh, Edinburgh, United Kingdom (UK)*
10. *Belgian Institute for Space Aeronomy (BIRA), Brussels, Belgium*
11. *Jet Propulsion Laboratory (JPL) / California Institute of Technology, Pasadena, CA, United States of America*
12. *The Inversion Lab, Hamburg, Germany*
13. *Deutsches Zentrum für Luft- und Raumfahrt (DLR), Oberpfaffenhofen, Germany*
14. *Max-Planck-Institute for Biogeochemistry (MPI-BGC), Jena, Germany*
15. *Lund University, Lund, Sweden*
16. *European Space Agency (ESA), ESRIN, Frascati, Italy*

ABSTRACT

The goal of the GHG-CCI project (http://www.esa-ghg-cci.org/) of ESA's Climate Change Initiative (CCI) is to generate global atmospheric satellite-derived carbon dioxide (CO_2) and methane (CH_4) data sets as needed to improve our understanding of the regional sources and sinks of these important greenhouse gases (GHG). Here we present an overview about the latest data set called Climate Research Data Package No. 3 (CRDP3). We focus on the GHG-CCI project core data products, which are near-surface-sensitive column-averaged dry air mole fractions of CO_2 and CH_4, denoted XCO_2 (in ppm) and XCH_4 (in ppb) retrieved from SCIAMACHY/ENVISAT (2002-2012) and TANSO-FTS/GOSAT (2009-today) nadir mode radiance observations in the near-infrared/shortwave-infrared spectral region. The GHG-CCI products are primarily individual sensor Level 2 products. However, we also generate merged Level 2 products ("EMMA products"). Here we also present a first GHG-CCI Level 3 product, namely XCO_2 and XCH_4 in Obs4MIPs format (monthly, 5^ox5^o).

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 all 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; Le Quéré et al., 2015), and despite efforts to reduce CO_2 emissions, atmospheric CO_2 continues to increase with approximately 2 ppm/year (Fig. 1). Appropriate knowledge concerning the various anthropogenic and natural CO_2 sources and sinks is needed for reliable prediction of the future climate of our planet. This is also true for methane (CH_4), whose various natural and anthropogenic sources are also only poorly understood (e.g., IPCC, 2013; Kirschke et al., 2013).

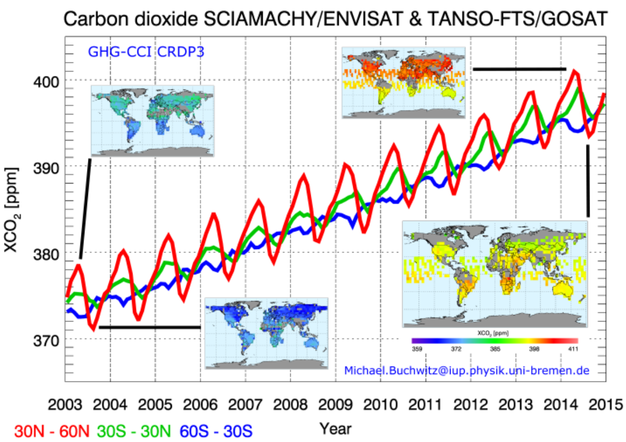

Fig. 1: (a) Timeseries of GHG-CCI CRDP3 XCO_2 in 3 latitude bands (see bottom left, e.g., the red line corresponds to northern mid-latitudes) and spatial maps for selected months at 5^ox5^o resolution obtained from merging the individual SCIAMACHY and GOSAT GHG-CCI XCO_2 Level 2 data products.

The main 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 (e.g., Reuter et al., 2014a, Bergamaschi et al., 2013, and references given therein). The GHG-CCI project generates 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".

The GHG-CCI data products have been used to address a number of scientifically important carbon and climate issues (e.g., Schneising et al., 2013, 2014a, 2014b; Reuter et al., 2014a, 2014b; Chevallier et al., 2014a; Buchwitz et al., 2015b; Detmers et al., 2015; Feng et al., 2016). A list of GHG-CCI peer-reviewed publications is available from the GHG-CCI website (http://www.esa-ghg-cci.org -> Publications). As can be seen from that website, currently (May 2016) 53 peer-reviewed publications have been identified, where GHG-CCI data sets have been used. In the following we present an overview about the new CRDP3 data set.

2. OVERVIEW CRDP3 DATA SET

Table 1 presents an overview about the GHG-CCI CRDP3 data products and Tab. 2 presents additional details on the GHG-CCI core retrieval algorithms and corresponding Level 2 data products retrieved from SCIAMACHY/ENVISAT (Burrows et al., 1995; Bovensmann et al., 1999) and TANSO-FTS/GOSAT (Kuze et al., 2009; Yoshida et al., 2013). As can be seen, for (nearly) all core products listed in Tab. 2 a baseline algorithm and an alternative algorithm and corresponding data product has been defined. We encourage the users of our data products to take advantage of this. For users who want or can use only one product we recommend to use the baseline product. Note however, that the baseline product is not necessarily the best product for all applications. For example, the CO2_SCI_BESD product has typically higher precision and accuracy compared to the CO2_SCI_WFMD product but the BESD product is relatively sparse compared to the WFMD product. For some applications the WFMD product may therefore be the better or even the only choice. In general we recommend to use both products to investigate to what extent conclusions drawn are robust w.r.t. to algorithmic choices and tradeoffs, which have to be made when implementing a retrieval algorithm as complex as the GHG-CCI retrieval algorithms. Note that the product format is essentially identical for all GHG-CCI core products listed in Tab. 2. To achieve this, all GHG-CCI core products have been generated according to the GHG-CCI Product Specification Document (PSD, version 3) (Buchwitz et al., 2014). This means that if a user is able to read and use one product, he/she can easily switch to another product.

For each product detailed information is available on the GHG-CCI Main Data Products website (http://www.esa-ghg-cci.org/sites/default/files/documents/public/documents/GHG-CCI_DATA.html) such as Product User Guide (PUG), Comprehensive Error Characterization Report (CECR) and Algorithm Theoretical Baseline Document (ATBD). Furthermore, two main documents are available covering all CRDP3 products: The Product Validation and Intercomparison Report (PVIR, version 4) (Buchwitz et al., 2016), written by the GHG-CCI validation and retrieval teams, and the Climate Assessment Report (CAR, version 3) (Chevallier et al., 2016), written by the GHG-CCI Climate Research Group (CRD), which documents the initial user assessment of the CRDP3 data set and contains model comparisons and CO_2 and CH_4 regional flux inversion results. As shown in document PVIR, the XCO_2 and XCH_4 data products are very stable, i.e., no long term drifts have been identified. However, some issues have been identified with SCIAMACHY XCH_4 in particular after mid 2010 due to detector degradation (e.g., the CH4_SCI_IMAP product contains an approx. 20 ppb "jump" mid 2010). As also shown, the GCOS accuracy requirements are met for XCO_2 (< 1 ppm) and XCH_4 (< 10 ppb) (with the exception of SCIAMACHY during later years due to detector issues in the spectral region used for methane retrieval), not however the more demanding requirement of the GHG-CCI CRG for XCO_2 (< 0.5 ppm) as formulated in the GHG-CCI User Requirements Document (URD, version 2) (Chevallier et al., 2014b).

An overview about the XCO_2 data set has already been presented in Fig. 1. Fig. 2 shows a higher resolution map for south-east Asia obtained by gridding the CO2_SCI_BESD product 0.5^ox0.5^o during 2010-2011. Note that all GHG-CCI data products are strictly quality filtered which essentially removes all observations which are affected by clouds. This is important in order to meet the demanding accuracy requirement. As a consequence, maps typically show a significant fraction of spatial gaps, even for multi-year averages. Fig. 3 shows the corresponding map for GOSAT (note that 2010-2011 are the two years where data from both sensors overlap). As can be seen, the GOSAT map is even sparser (over land) due to the sampling strategy of GOSAT combined with the fact that the GOSAT ground pixel size is smaller compared to SCIAMACHY (10 km versus approx. 50 km) and because the number of observations per time is much higher for SCIAMACHY compared to GOSAT. As can be seen, the spatial patterns agree reasonably well, with highest XCO_2 over large parts of south-east China but also over Thailand. Note that perfect agreement is cannot be expected due to several reasons (e.g., different spatio-temporal resolution and sampling).

GHG-CCI Climate Research Data Package (CRDP#3)															
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**								■	■	■	■	■		
XCH4_EMMA	**XCH_4**								■	■	■	■	■	■	
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)**	■	■	■	■	■	■	■	■	■	■	■			
CH4_MIPAS	**CH_4 (2)**	■	■	■	■	■	■	■	■	■	■	■			
CO2_AIRS	**CO_2 (1)**		▭	▭	▭	▭	▭								
CO2_ACEFTS	**CO_2 (2)**			▭	▭	▭									

Comments:

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

CRDP#3 ■
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), OCFP & OCPR (UoL-PR)
XCO2_EMMA: Various (SCIA & GOSAT merged)
XCH4_EMMA: Various (GOSAT merged)

Tab. 1: Overview about the GHG-CCI CRDP3 Level 2 CO_2 and CH_4 data products. Note that EMMA refers to the Ensemble Median Algorithm of Reuter et al., 2013. The EMMA products are merged SCIAMACHY and GOSAT Level 2 products. In this publication we focus on the GHG-CCI core products (ECA products). For details on the Additional Constraints Algorithm (ACA) products from, e.g., IASI and MIPAS, please see the GHG-CCI website.

GHG-CCI CRDP#3: ECV Core Algorithm (ECA) Products				
Algorithm / Product ID	**Product**	**Sensor**	**Algorithm Institute**	**Comment (Reference)**
CO2_SCI_BESD	XCO_2	SCIAMACHY	BESD IUP	*SCIAMACHY XCO_2 baseline product (Reuter et al., 2011)*
CO2_SCI_WFMD	XCO_2	SCIAMACHY	WFM-DOAS IUP	*SCIAMACHY XCO_2 alternative product (Schneising et al., 2011)*
CO2_GOS_OCFP	XCO_2	TANSO	UoL-FP UoL	*GOSAT XCO_2 product baseline product (Cogan et al., 2012)*
CO2_GOS_SRFP	XCO_2	TANSO	RemoteC SRON/KIT	*GOSAT XCO_2 alternative product (Butz et al., 2011)*
CH4_SCI_WFMD	XCH_4	SCIAMACHY	WFM-DOAS IUP	*SCIAMACHY XCH_4 proxy product (baseline not yet decided)(Schneising et al., 2011)*
CH4_SCI_IMAP	XCH_4	SCIAMACHY	IMAP SRON/JPL	*SCIAMACHY XCH_4 proxy product (baseline not yet decided) (Frankenberg et al., 2011)*
CH4_GOS_OCPR	XCH_4	TANSO	UoL-PR UoL	*GOSAT XCH_4 proxy baseline product (Parker et al., 2011)*
CH4_GOS_SRPR	XCH_4	TANSO	RemoteC SRON/KIT	*GOSAT XCH_4 proxy alternative product (Butz et al., 2010)*
CH4_GOS_SRFP	XCH_4	TANSO	RemoteC SRON/KIT	*GOSAT XCH_4 full physics baseline product (Butz et al., 2011)*
CH4_GOS_OCFP	XCH_4	TANSO	UoL-PR UoL	*GOSAT XCH_4 full physics alternative product (Parker et al., 2011)*

Tab. 2: Overview about the GHG-CCI CRDP3 XCO_2 and XCH_4 retrieval algorithms and corresponding data products. For a description and discussion of "proxy" and "full physics" retrievals see, e.g., Schepers et al., 2012. For details see GHG-CCI website.

Figure 4 presents an overview about the GHG-CCI CRDP3 XCH_4 data set. As can be seen, atmospheric methane is essentially constant (apart from the seasonal cycle) until about 2007 but shows an approximate linear increase afterwards. Why methane was stable for several years before 2007 and why it started to increase after 2007 is still not entirely clear. Very likely the current increase is due to a number of reasons such as increasing emissions from fossil fuel related sources but also from anthropogenic and natural biogenic sources (agriculture, wetlands) (e.g., Rigby et al., 2008; Dlugokencky et al., 2009; Schneising et al., 2011; Simpson et al., 2012; Bergamaschi et al., 2013; Kirschke et al., 2013; Houweling et al., 2014; Nisbet et al., 2014; Schaefer et al., 2016). Figure 4 shows that the increase is quite similar in all latitude bands. Concerning spatial pattern, Fig. 5 shows two spatial maps of 3-year averages of SCIAMACHY XCH_4, for 2003-2005 and 2008-2010, i.e., for time periods before and after 2007. The main difference between the two maps is a general increase of XCH_4 by about 30-35 ppb (nearly 2%).

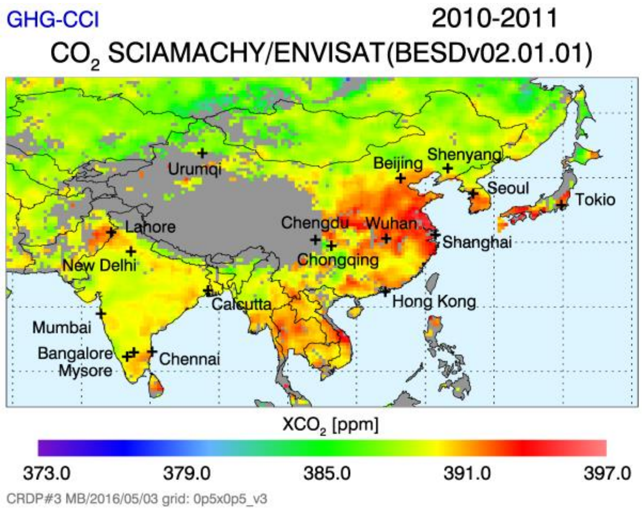

Fig. 2: SCIAMACHY XCO_2 over south-east Asia 2010-2011.

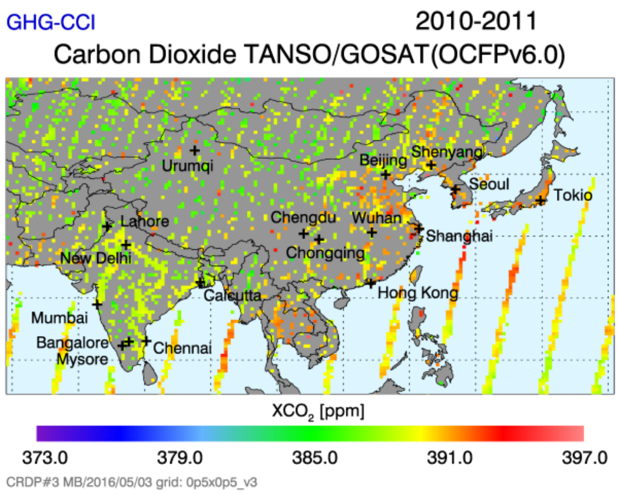

Fig. 3: As Fig. 2 but for GOSAT.

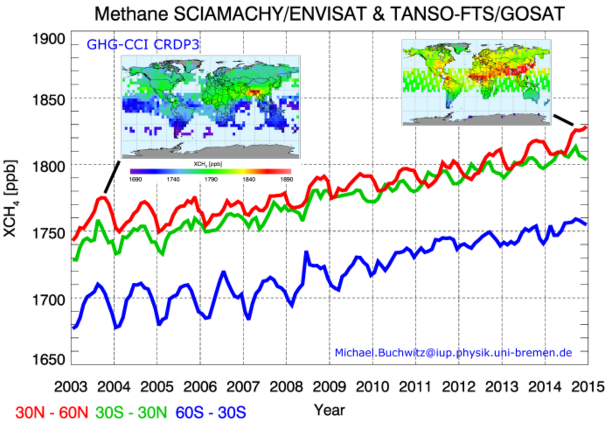

Fig. 4: As Fig. 1 but for XCH_4.

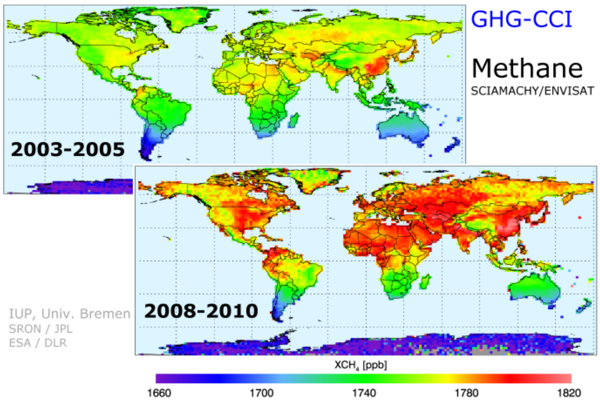

Fig. 5: SCIAMACHY XCH_4 2003-2005 (top left) and 2008-2010 (bottom right).

3. ONGOING ACTIVITIES AND FUTURE PLANS

Among the ongoing activities within the GHG-CCI project are two major ones, namely the generation of XCO_2 and XCH_4 Level 3 products in Obs4MIPs format and the preparation for the generation of CRDP4. These two topics are briefly addressed in the following two sub-sections.

GHG-CCI team members are also involved in the EU Copernicus Climate Monitoring Service (CAMS, http://www.ecmwf.int/en/about/what-we-do/copernicus/copernicus-atmosphere-monitoring-service) by generating XCO_2 and XCH_4 products in quasi-Near-Real-Time (NRT) (currently within 4 days after GOSAT measurement). For example, Univ. Bremen is responsible for GOSAT XCO_2 retrievals (Heymann et al., 2015; Massart et al., 2016), which are delivered to ECMWF and which are available from the GOSAT/BESD website (http://www.iup.uni-bremen.de/~heymann/besd_gosat.php). These CAMS activities are highly complementary to the GHG-CCI activities, which focus on reprocessing to generate long-term consistent data sets with highest possible accuracy and precision, whereas the CAMS focus is on fast processing and delivery to meet the demanding CAMS NRT requirement.

Furthermore, GHG-CCI team members are also members of NASA's OCO-2 (Crisp et al., 2004) Science Team. Currently, focus is on comparisons of the GHG-CCI XCO_2 products with OCO-2 XCO_2 products and on initial OCO-2 XCO_2 retrievals. GHG-CCI team members are also involved in ESA's Sentinel-5-Precursor (S5P) mission (Veefkind et al., 2012) which will deliver XCH_4 at high spatial resolution (approx. 7 km) with very good spatial coverage in the future.

3.1 Obs4MIPs products

Obs4MIPs (Observations for Model Intercomparisons Project, https://www.earthsystemcog.org/projects/obs4mips/) is an activity to make observational products more accessible for climate model intercomparisons. Within this Obs4MIPs project a data format has been specified appropriate for comparisons with the output of climate models. Within GHG-CCI activities are ongoing to generate data products meeting the Obs4MIPs requirements. Initial XCO_2 and XCH_4 data products in Obs4MIPs format have been generated based on the GHG-CCI CRDP3 data set. These products have been generated from the individual SCIAMACHY and GOSAT Level 2 products listed in Tab. 2. Details on these products including links to initial (not yet officially released) product files are given in two Technical Notes (Buchwitz and Reuter, 2016a, 2016b). The Obs4MIPs files are NetCDF files (one for XCO_2 and one for XCH_4) which contain monthly averages at 5^ox5^o spatial resolution covering the time period 2003-2014. Figures 1 and 4 have been generated based on these Obs4MIPs products. As shown in Buchwitz and Reuter, 2016a, 2016b, also an initial validation of these products has been carried out using Total Carbon Column Observation Network (TCCON, Wunch et al., 2011, 2015) ground-based observations. Summary results are shown in Fig. 6 (for XCO_2) and Fig. 7 (for XCH_4). The comparisons are based on monthly averaged TCCON data. As can be seen, the agreement with TCCON is 0.3 +/- 1.2 ppm for XCO_2 and 2 +/- 11 ppb for XCH_4.

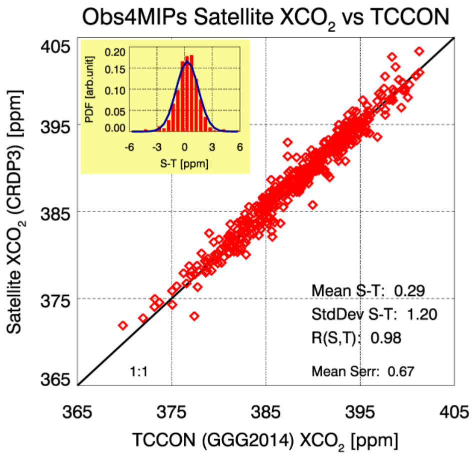

Fig. 6: Comparison of the initial GHG-CCI Obs4MIPs XCO_2 product obtained from the CRDP3 data set with TCCON ground-based observations.

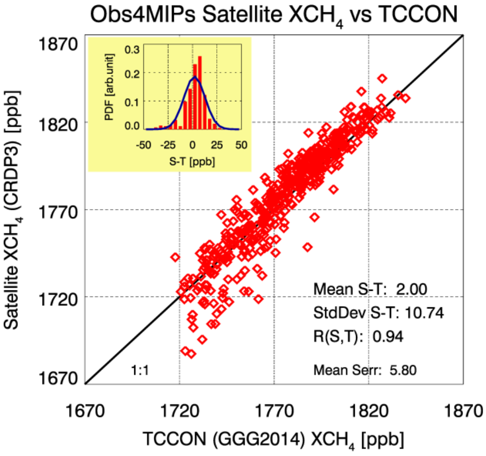

Fig. 7: As Fig. 6 but for Obs4MIPs XCH_4.

3.2 CRDP No. 4

Currently the GHG-CCI retrieval team is working on the generation of the next data set, i.e., on CRDP4. CRDP4 will be extended in time compared to CRDP3 by adding year 2015 data. Very likely all data products will be regenerated by reprocessing all data of the entire time period with improved retrieval algorithms to (further) increase the data quality. CRDP4 will be available along with all relevant documents via the GHG-CCI website end of February 2017.

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REFERENCES

1. Bergamaschi, P., Houweling, H., Segers, A., et al., Atmospheric CH_4 in the first decade of the 21st century: Inverse modeling analysis using SCIAMACHY satellite retrievals and NOAA surface measurements, *J. Geophys. Res.*, 118, 7350-7369, doi:10.1002/jrgd.50480, 2013.
2. Bovensmann, H., Burrows, J. P., Buchwitz, M., et al., SCIAMACHY - Mission objectives and measurement modes, *J. Atmos. Sci.*, 56 (2), 127-150, 1999.
3. Buchwitz, M., Detmers, R., Boesch, H., et al., Product Specification Document for the GHG-CCI project of ESA's Climate Change Initiative, version 3 (PSDv3), 6. June 2014, http://www.esa-ghg-cci.org/index.php?q=webfm_send/160, 2014.
4. Buchwitz, M., Reuter, M., Schneising, O., et al., The Greenhouse Gas Climate Change Initiative (GHG-CCI): comparison and quality assessment of near-surface-sensitive satellite-derived CO_2 and CH_4 global data sets, *Remote Sensing of Environment*, 162, 344-362, doi:10.1016/j.rse.2013.04.024, 2015a.
5. Buchwitz, M., Reuter, M., Schneising, O., et al., THE GREENHOUSE GAS PROJECT OF ESA'S CLIMATE CHANGE INITIATIVE (GHG-CCI): OVERVIEW, ACHIEVEMENTS AND FUTURE PLANS, The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XL-7/W3, 2015 36th International Symposium on Remote Sensing of Environment, 11–15 May 2015, Berlin,

Germany, http://www.esa-ghg-cci.org/?q=webfm_send/262, 2015b.

6. Buchwitz, M., Dils, B., Boesch, H., Crevoisier, C., Detmers, D., Frankenberg, C., Hasekamp, O., Hewson, W., Laeng, A., Noël, S., Notholt, J., Parker, R., Reuter, M., Schneising, O., ESA Climate Change Initiative (CCI) Product Validation and Intercomparison Report (PVIR) for the Essential Climate Variable (ECV) Greenhouse Gases (GHG) for data set Climate Research Data Package No. 3 (CRDP#3), Version 4.0, 24. Feb. 2016, 2016. (link: http://www.esa-ghg-cci.org/?q=webfm_send/300).
7. Buchwitz, M., Reuter, M., Merged SCIAMACHY/ENVISAT and TANSO-FTS/GOSAT atmospheric column-average dry-air mole fraction of CO_2 (XCO_2), Technical Note, Version: 1 (rev 1), 22-April-2016, 2016a. Link: http://www.esa-ghg-cci.org/?q=webfm_send/319
8. Buchwitz, M., Reuter, M., Merged SCIAMACHY/ENVISAT and TANSO-FTS/GOSAT atmospheric column-average dry-air mole fraction of CH_4 (XCH_4), Technical Note, Version: 1 (rev 0), 22-April-2016, 2016b. Link: http://www.esa-ghg-cci.org/?q=webfm_send/320
9. Burrows, J. P., Hölzle, E., Goede, A. P. H., Visser, H., and Fricke, W., SCIAMACHY - Scanning Imaging Absorption Spectrometer for Atmospheric Chartography, *Acta Astronaut*., 35(7), 445–451, doi:10.1016/0094-5765(94)00278-t, 1995.
10. Butz, A., Hasekamp, O. P., Frankenberg, C., Vidot, J., and Aben, I., CH_4 retrievals from space-based solar backscatter measurements: Performance evaluation against simulated aerosol and cirrus loaded scenes, *J. Geophys. Res*., Volume 115, Issue D24, 27, DOI: 10.1029/2010JD014514, 2010.
11. Butz, A., Guerlet, S., Hasekamp, O., et al., Toward accurate CO_2 and CH_4 observations from GOSAT, *Geophys. Res. Lett.*, doi:10.1029/2011GL047888, 2011.
12. Canadell, J. G., Ciais, P., Dhakal, S., et al., Interactions of the carbon cycle, human activity, and the climate system: a research portfolio, *Curr. Opin. Environ. Sustainabil*., 2, 301–311, 2010.
13. CEOS, CEOS Strategy for Carbon Observations from Space. The Committee on Earth Observation Satellites (CEOS) Response to the Group on Earth Observations (GEO) Carbon Strategy., April 2014 (issued date: September 30, 2014), 2014.
14. Chevallier, F., Palmer, P.I., Feng, L., Boesch, H., O'Dell, C.W., Bousquet, P., Towards robust and consistent regional CO_2 flux estimates from in situ and space-borne measurements of atmospheric CO_2, *Geophys. Res. Lett.*, 41, 1065-1070, DOI: 10.1002/2013GL058772, 2014a.
15. Chevallier, F., Buchwitz, M., Bergamaschi, et al., User Requirements Document for the GHG-CCI project of ESA's Climate Change Initiative, version 2 (URDv2), 28. August 2014, http://www.esa-ghg-cci.org/?q=webfm_send/173, 2014b.
16. Chevallier, F., M. Alexe, P. Bergamaschi, D. Brunner, L. Feng, S. Houweling, T. Kaminski, W. Knorr, T. T. van Leeuwen, J. Marshall, P. I. Palmer, M. Scholze, A.-M. Sundström, M. Voßbeck, ESA Climate Change Initiative (CCI) Climate Assessment Report (CAR) for Climate Research Data Package No. 3 (CRDP#3) of the Essential Climate Variable (ECV) Greenhouse Gases (GHG), Version 3, pp. 94, 3 May 2016, 2016. Link: http://www.esa-ghg-cci.org/?q=webfm_send/318
17. Ciais, P., Dolman, A. J., Dargaville, R., Barrie, L., Butler, J., Canadell, J., & Moriyama, T., GEO Carbon Strategy. Rome: GEO Secretariat, Geneva / FAO, 2010.
18. Ciais, P., Dolman, A. J., Bombelli, A., et al., Current systematic carbon cycle observations and needs for implementing a policy-relevant carbon observing system, *Biogeosciences*, 11, 3547-3602, www.biogeosciences.net/11/3547/2014/, doi:10.5194/bg-11-3547-2014, 2014.
19. Cogan, A. J., Boesch, H., Parker, R. J., et al., Atmospheric carbon dioxide retrieved from the Greenhouse gases Observing SATellite (GOSAT): Comparison with ground-based TCCON observations and GEOS-Chem model calculations, *J. Geophys. Res.*, 117, D21301, doi:10.1029/2012JD018087, 2012.
20. Crisp, D., Atlas, R. M., Bréon, F.-M., Brown, L. R., Burrows, J. P., Ciais, P., Connor, B. J., Doney, S. C., Fung, I. Y., Jacob, D. J., Miller, C. E., O'Brien, D., Pawson, S., Randerson, J. T., Rayner, P., Salawitch, R. J., Sander, S. P., Sen, B., Stephens, G. L., Tans, P. P., Toon, G. C., Wennberg, P. O., Wofsy, S. C., Yung, Y. L., Kuang, Z., Chudasama, B., Sprague, G., Weiss, B., Pollock, R., Kenyon, D., and Schroll, S., The Orbiting Carbon Observatory (OCO) mission, *Adv. Space Res*., 34, 700–709, doi:10.1016/j.asr.2003.08.062, 2004.
21. Detmers, R. G., O. Hasekamp, I. Aben, S. Houweling, T. T. van Leeuwen, A. Butz, J. Landgraf, P. Koehler, L. Guanter, and B. Poulter, Anomalous carbon uptake in Australia as seen by GOSAT, Geophys. Res. Lett., 42, doi:10.1002/2015GL065161, 2015.
22. Dlugokencky, E. J., Bruhwiler, L., White, J. W. C., et al., Observational constraints on recent increases in the atmospheric CH_4 burden, *Geophys. Res. Lett.*, 36, L18803, doi:10.1029/2009GL039780, 2009.
23. Feng, L., P. I. Palmer, R. J. Parker, N. M. Deutscher, D. G. Feist, R. Kivi, I. Morino, and R. Sussmann, Estimates of European uptake of CO_2 inferred from GOSAT XCO_2 retrievals: sensitivity to measurement bias inside and outside Europe, *Atmos. Chem. Phys*., 16, 1289-1302, doi:10.5194/acp-16-1289-2016, 2016.
24. Frankenberg, C., Aben, I., Bergamaschi, P., et al., Global column-averaged methane mixing ratios from 2003 to 2009 as derived from SCIAMACHY: Trends and variability, *J. Geophys. Res*., doi:10.1029/2010JD014849, 2011.
25. GCOS (Global Climate Observing System): SYSTEMATIC OBSERVATION REQUIREMENTS FOR SATELLITE-BASED DATA PRODUCTS FOR CLIMATE - 2011 Update - Supplemental details to the satellite-based component of the "Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (2010 Update)", GCOS-154, 2011.
26. Heymann, J., M. Reuter, M. Hilker, M. Buchwitz, O. Schneising, H. Bovensmann, J. P. Burrows, A. Kuze, H. Suto, N. M. Deutscher, M. K. Dubey, D. W. T. Griffith, F. Hase, S. Kawakami, R. Kivi, I. Morino, C. Petri, C. Roehl, M. Schneider, V. Sherlock, R. Sussmann, V. A. Velazco, T. Warneke, and D. Wunch, Consistent satellite XCO_2 retrievals from SCIAMACHY and GOSAT using the BESD algorithm, Atmos. Meas. Tech., 8, 2961-2980, 2015.
27. Hollmann, R., Merchant, C. J., Saunders, R., et al., The ESA Climate Change Initiative: satellite data records for essential climate variables, *Bulletin of the American Meteorological Society (BAMS)*, 0.1175/BAMS-D-11-00254.1, 2013.
28. Houweling, S., M. Krol, P. Bergamaschi et al., A multi-year methane inversion using SCIAMACHY, accounting for systematic errors using TCCON measurements, *Atmos. Chem. Phys*., 14, 3991-4012, http://www.atmos-chem-phys.net/14/3991/2014/, doi:10.5194/acp-14-3991-2014, 2014.
29. IPCC, Climate Change 2013: The Physical Science Basis, Working Group I Contribution to the Fifth Assessment

Report of the Intergovernmental Report on Climate Change, http://www.ipcc.ch/report/ar5/wg1/, 2013.
30. Kirschke, S., Bousquet, P., Ciais, P., et al., Three decades of global methane sources and sinks, *Nat. Geosci*., 6, 813–823, doi:10.1038/ngeo1955, 2013.
31. Kuze, A., Suto, H., Nakajima, M., and Hamazaki, T., Thermal and near infrared sensor for carbon observation Fourier-transform spectrometer on the Greenhouse Gases Observing Satellite for greenhouse gases monitoring, *Appl. Opt*., 48, 6716–6733, 2009.
32. Le Quéré, C., Moriarty, R., Andrew, R. M., et al., Global carbon budget 2015, Earth Syst. Sci. Data, 7, 349–396, www.earth-syst-sci-data.net/7/349/2015/, doi:10.5194/essd-7-349-2015, 2015.
33. Massart, S., A. Agustí-Panareda, J. Heymann, M. Buchwitz, F. Chevallier, M. Reuter, M. Hilker, J. P. Burrows, N. M. Deutscher, D. G. Feist, F. Hase, R. Sussmann, F. Desmet, M. K. Dubey, D. W. T. Griffith, R. Kivi, C. Petri, M. Schneider, V. A. Velazco, Ability of the 4-D-Var analysis of the GOSAT BESD XCO_2 retrievals to characterize atmospheric CO_2 at large and synoptic scales, *Atmos. Chem. Phys*., 16, 1653-1671, doi:10.5194/acp-16-1653-2016, 2016.
34. Nisbet, E., Dlugokencky, E., Bousquet, P., Methane on the rise – again, *Science*, 343, 493–495, doi:10.1126/science.1247828, 2014.
35. Parker, R., Boesch, H., Cogan, A., et al., Methane Observations from the Greenhouse gases Observing SATellite: Comparison to ground-based TCCON data and Model Calculations, *Geophys. Res. Lett*., doi:10.1029/2011GL047871, 2011.
36. Reuter, M., Bovensmann, H., Buchwitz, M., et al., Retrieval of atmospheric CO_2 with enhanced accuracy and precision from SCIAMACHY: Validation with FTS measurements and comparison with model results, *J. Geophys. Res*., 116, D04301, doi:10.1029/2010JD015047, 2011.
37. Reuter, M., Boesch, H., Bovensmann, H., et al., A joint effort to deliver satellite retrieved atmospheric CO_2 concentrations for surface flux inversions: the ensemble median algorithm EMMA, *Atmos. Chem. Phys*., 13, 1771-1780, 2013.
38. Reuter, M., Buchwitz, M., Hilker, M., et al., Satellite-inferred European carbon sink larger than expected, *Atmos. Chem. Phys*., 14, 13739-13753, www.atmos-chem-phys.net/14/13739/2014/, doi:10.5194/acp-14-13739-2014, 2014a.
39. Reuter, M., Buchwitz, M., Hilboll, A., et al., Decreasing emissions of NOx relative to CO_2 in East Asia inferred from satellite observations, *Nature Geoscience*, 28 Sept. 2014, doi:10.1038/ngeo2257, pp.4, 2014b.
40. Rigby, M., Prinn, R. G., Fraser, P. J., et al., Renewed growth of atmospheric methane, *Geophys. Res. Lett*., 35, L22805, doi:10.1029/2008GL036037, 2008.
41. Schaefer, H., Fletcher, S. E. M., Veidt, C. et al., A 21st-century shift from fossil-fuel to biogenic methane emissions indicated by $^{13}CH_4$, *Science*, Vol 352, Issue 6281, 80-84, 2016.
42. Schepers, D., Guerlet, S., Butz, A., et al., Methane retrievals from Greenhouse Gases Observing Satellite (GOSAT) shortwave infrared measurements: Performance comparison of proxy and physics retrieval algorithms, *J. Geophys. Res*., 117, D10307, doi:10.1029/2012JD017549, 2012.
43. Schneising, O., Buchwitz, M., Reuter, M., et al., Long-term analysis of carbon dioxide and methane column-averaged mole fractions retrieved from SCIAMACHY, *Atmos. Chem. Phys*., 11, 2881-2892, 2011.
44. Schneising, O., Bergamaschi, P., Bovensmann, H., et al., Atmospheric greenhouse gases retrieved from SCIAMACHY: comparison to ground-based FTS measurements and model results, *Atmos. Chem. Phys*., 12, 1527-1540, 2012.
45. Schneising, O., Heymann, J., Buchwitz, M., Reuter, M., Bovensmann, H., and Burrows, J. P., Anthropogenic carbon dioxide source areas observed from space: assessment of regional enhancements and trends, *Atmos. Chem. Phys*., 13, 2445-2454, 2013.
46. Schneising, O., Reuter, M., Buchwitz, M., Heymann, J., Bovensmann, H., and Burrows, J. P., Terrestrial carbon sink observed from space: variation of growth rates and seasonal cycle amplitudes in response to interannual surface temperature variability, *Atmos. Chem. Phys*., 14, 133-141, 2014a.
47. Schneising, O., Burrows, J. P., Dickerson, R. R., Buchwitz, M., Reuter, M., Bovensmann, H., Remote sensing of fugitive methane emissions from oil and gas production in North American tight geologic formations, *Earth's Future*, 2, DOI: 10.1002/2014EF000265, pp. 11, 2014b.
48. Simpson, I. J., Anderson, M. P. S., Meinardi, S., et al., Long-term decline of global atmospheric ethane concentrations and implications for methane, *Nature*, Vol 488, 490-494, 2012.
49. Veefkind, J. P., Aben, I., McMullan, K., Förster, H., De Vries, J., Otter, G., Claas, J., Eskes, H. J., De Haan, J. F., Kleipool, Q., Van Weele, M., Hasekamp, O., Hoogeveen, R., Landgraf, J., Snel, R., Tol, P.,Ingmann, P., Voors, R., Kruizinga, B., Vink, R., Visser, H., and Levelt, P. F., TROPOMI on the ESA Sentinel-5 Precursor: A GMES mission for global observations of the atmospheric composition for climate, air quality and ozone layer applications. Rem. Sens. Environment, 120:70–83, 2012.
50. Wunch, D., Toon, G. C., Blavier, J.-F., et al., The Total Carbon Column Observing Network, *Phil. Trans. R. Soc. A*, 369, 2087–2112, doi:10.1098/rsta.2010.0240, 2011.
51. Wunch, D., Toon, G. C., Sherlock, V., Deutscher, N. M, Liu, X., Feist, D. G., and Wennberg, P. O., The Total Carbon Column Observing Network's GGG2014 Data Version. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA, available at: doi:10.14291/tccon.ggg2014.documentation.R0/1221662, 2015.
52. Yoshida, Y., Kikuchi, N., Morino, I., et al., Improvement of the retrieval algorithm for GOSAT SWIR XCO_2 and XCH_4 and their validation using TCCON data, *Atmos. Meas. Tech*., 6, 1533–1547, doi:10.5194/amt-6-1533-2013, 2013.