



Algorithm Theoretical Basis Document (ATBD) – Main document for Greenhouse Gas (GHG: CO₂ & CH₄) data set CDR7 (01.2003-12.2022)

C3S2_312a_Lot2_DLR – Atmosphere

Issued by: Michael Buchwitz, University of Bremen,
Institute of Environmental Physics (IUP)

Date: 13/09/2023

Ref: C3S2_312a_Lot2_D-WP1_ATBD-2023-GHG_MAIN_v7.1

Official reference number service contract: 2021/C3S2_312a_Lot2_DLR/SC1





This document has been produced in the context of the Copernicus Climate Change Service (C3S). The activities leading to these results have been contracted by the European Centre for Medium-Range Weather Forecasts, operator of C3S on behalf on the European Union (Contribution Agreement signed on 22/07/2021). All information in this document is provided “as is” and no guarantee of warranty is given that the information is fit for any particular purpose. The users thereof use the information at their sole risk and liability. For the avoidance of all doubt, the European Commission and the European Centre for Medium-Range Weather Forecasts have no liability in respect of this document, which is merely representing the author’s view.



Contributors

**INSTITUTE OF ENVIRONMENTAL PHYSICS (IUP),
UNIVERSITY OF BREMEN, BREMEN, GERMANY
(IUP)**

M. Buchwitz
M. Reuter
O. Schneising-Weigel
H. Boesch
A. Di Noia

**SRON NETHERLANDS INSTITUTE FOR SPACE RESEARCH,
LEIDEN, THE NETHERLANDS
(SRON)**

A. Barr
T. Borsdorff
J. Landgraf

**CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE (CNRS),
LABORATOIRE DE METEOROLOGIE DYNAMIQUE (LMD),
PALAISEAU, FRANCE
(LMD/CNRS)**

C. Crevoisier
N. Meilhac



History of modifications

Version	Date	Description of modification	Chapters / Sections
1.1	20-October-2017	New document for data set CDR1 (temporal coverage: 2003-2016)	All
2.0	16-October-2018	Update for data set CDR2 (temporal coverage: 2003-2017)	All
3.0	12-August-2019	Update for data set CDR3 (temporal coverage: 2003-2018)	All
3.1	03-November-2019	Update after review: Correction of typos and broken links	All
4.0	18-August-2020	Update for data set CDR4 (temporal coverage: 2003-2019)	All
5.0	17-February-2021	Update for data set CDR5 (temporal coverage: 01.2003-06.2020)	All
6.0 Initial Draft	18-February-2022	Initial draft for data set CDR6	All
6.0	4-August-2022	Update for data set CDR6 (temporal coverage: 01.2003-12.2021)	All
6.1	25-November-2022	Update after review (use of new template, various mostly minor improvements at several places)	All
6.2	31-January-2023	Minor improvements at various places taking into account feedback from 2 nd review	All
7.0 (Draft 1)	14-February-2023	Initial draft for data set CDR7 ("Delta-ATBD")	All
7.0 (Draft 2)	27-April-2023	Updates taking into account feedback from independent review	All
7.0 (Draft 4)	3-August-2023	Improved Draft after review	All
7.0	28-August-2023	Update for data set CDR7	All
7.1	13-September-2023	Minor improvements after review	All



List of datasets covered by this document

Deliverable ID	Product title (*)	Product type (CDR, ICDR)	Version number (§)	Delivery date
WP2-FDDP-GHG-v2	CO2_GOS_OCFP (ANNEX A)	CDR 7	7.3	31-Aug-2023
WP2-FDDP-GHG-v2	CH4_GOS_OCFP (ANNEX A)	CDR 7	7.3	31-Aug-2023
WP2-FDDP-GHG-v2	CH4_GOS_OCPR (ANNEX A)	CDR 7	9.0	31-Aug-2023
WP2-FDDP-GHG-v2	CO2_GO2_SRF (ANNEX B)	CDR 7	2.0.0	31-Aug-2023
WP2-FDDP-GHG-v2	CH4_GO2_SRF (ANNEX B)	CDR 7	2.0.0	31-Aug-2023
WP2-FDDP-GHG-v2	CH4_GO2_SRPR (ANNEX C)	CDR 7	2.0.1	31-Aug-2023
WP2-FDDP-GHG-v2	XCO2_EMMA, XCH4_EMMA, XCO2_OBS4MIPS, XCH4_OBS4MIPS (ANNEX D)	CDR 7	4.5	31-Aug-2023
WP2-FDDP-GHG-v2	CO2_IASA_NLIS, CH4_IASA_NLIS, CO2_IASB_NLIS, CH4_IASB_NLIS, CO2_IASC_NLIS, CH4_IASC_NLIS (ANNEX E) (#)	CDR 7	10.1 10.2 10.1 10.2 10.1 10.2	31-Aug-2023

(*) In brackets: see listed ANNEX to this MAIN document for details on listed product(s).

(#) ANNEX E also includes some information on product CO2_AIRS_NLIS (v3.0) but that product has been generated in a pre-cursor project and no assessments have been carried out in this project. Therefore, this product is not listed here.



Related documents

Reference ID	Document
D1	GCOS-154: Global Climate Observing System (GCOS): 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)”, December 2011, prepared by World Meteorological Organization (WMO), Intergovernmental Oceanographic Commission, United Nations Environment Programme (UNEP), International Council for Science, Doc.: GCOS 154, 2011. Link: http://cci.esa.int/sites/default/files/gcos-154.pdf
D2	GCOS-200: The Global Observing System for Climate: Implementation Needs, World Meteorological Organization (WMO), GCOS-200 (GOOS-214), pp. 325, 2016. Link: http://unfccc.int/files/science/workstreams/systematic_observation/application/pdf/gcos_ip_10oct2016.pdf
D3	ESA-CCI-GHG-URDv2.1: Chevallier, F., et al., User Requirements Document (URD), ESA Climate Change Initiative (CCI) GHG-CCI project, Version 2.1, 19 Oct 2016, 2016. Link: https://www.iup.uni-bremen.de/carbon_ghg/docs/GHG-CCIplus/URD/URDv2.1_GHG-CCI_Final.pdf
D4	TRD GAD GHG, 2022: Buchwitz, M., Aben, I., Armante, R., Boesch, H., Crevoisier, C., Hasekamp, O. P., Wu, L., Reuter, M., Schneising-Weigel, O., Target Requirement and Gap Analysis Document, Copernicus Climate Change Service (C3S) project on satellite-derived Essential Climate Variable (ECV) Greenhouse Gases (CO₂ and CH₄) data products (project C3S2_312a_Lot2), Version 5.0, 2-Dec-2022, pp. 83, 2022. Link: http://wdc.dlr.de/C3S_312b_Lot2/Documentation/GHG/C3S2_312a_Lot2_TRD-GAD_GHG_latest.pdf
D5	PUGS GHG, 2023: Buchwitz, M., Barr, A., Boesch, H., Borsdorff, T., Crevoisier, C., Di Noia, A., Hasekamp, O. P., Landgraf, J., Meilhac, N., Parker, R., Reuter, M., Schneising-Weigel, O.: Product User Guide and Specification (PUGS) – Main document for Greenhouse Gas (GHG: CO₂ & CH₄) data set CDR6 (01.2003-12.2021), C3S project C3S2_312a_Lot2_DLR, v6.3, 2023. Link: https://www.iup.uni-bremen.de/carbon_ghg/docs/C3S/CDR6_2003-2021/C3S2_312a_Lot2_D-WP2_PUGS-2022-GHG_MAIN_v6.3.pdf



Acronyms

Acronym	Definition
AIRS	Atmospheric Infrared Sounder
AMSU	Advanced Microwave Sounding Unit
ATBD	Algorithm Theoretical Basis Document
BESD	Bremen optimal ESTimation DOAS
CAR	Climate Assessment Report
C3S	Copernicus Climate Change Service
CCDAS	Carbon Cycle Data Assimilation System
CCI	Climate Change Initiative
CDR	Climate Data Record
CDS	(Copernicus) Climate Data Store
CMUG	Climate Modelling User Group (of ESA's CCI)
CRG	Climate Research Group
D/B	Data base
DOAS	Differential Optical Absorption Spectroscopy
EC	European Commission
ECMWF	European Centre for Medium Range Weather Forecasting
ECV	Essential Climate Variable
EMMA	Ensemble Median Algorithm
ENVISAT	Environmental Satellite (of ESA)
EO	Earth Observation
ESA	European Space Agency
EU	European Union
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FCDR	Fundamental Climate Data Record
FoM	Figure of Merit
FP	Full Physics retrieval method
FTIR	Fourier Transform InfraRed
FTS	Fourier Transform Spectrometer
GCOS	Global Climate Observing System
GEO	Group on Earth Observation
GEOSS	Global Earth Observation System of Systems
GHG	GreenHouse Gas
GOS	GOSAT
GO2	GOSAT-2
GOME	Global Ozone Monitoring Experiment
GMES	Global Monitoring for Environment and Security
GOSAT	Greenhouse Gases Observing Satellite
GOSAT-2	Greenhouse Gases Observing Satellite 2



IASI	Infrared Atmospheric Sounding Interferometer
IMAP-DOAS (or IMAP)	Iterative Maximum A posteriori DOAS
IPCC	International Panel in Climate Change
IUP	Institute of Environmental Physics (IUP) of the University of Bremen, Germany
JAXA	Japan Aerospace Exploration Agency
JCGM	Joint Committee for Guides in Metrology
L1	Level 1
L2	Level 2
L3	Level 3
L4	Level 4
LMD	Laboratoire de Météorologie Dynamique
MACC	Monitoring Atmospheric Composition and Climate, EU GMES project
NA	Not applicable
NASA	National Aeronautics and Space Administration
NetCDF	Network Common Data Format
NDACC	Network for the Detection of Atmospheric Composition Change
NIES	National Institute for Environmental Studies
NIR	Near Infra Red
NLIS	LMD/CNRS neuronal network mid/upper tropospheric CO ₂ and CH ₄ retrieval algorithm
NOAA	National Oceanic and Atmospheric Administration
Obs4MIPs	Observations for Climate Model Intercomparisons
OCFP	OCO-2 Full Physics (FP) algorithm (used by Univ. Leicester)
OCO	Orbiting Carbon Observatory
OCPR	OCO-2 Proxy (PR) algorithm (used by Univ. Leicester)
OE	Optimal Estimation
PBL	Planetary Boundary Layer
ppb	Parts per billion
ppm	Parts per million
PQAD	Product Quality Assurance Document
PQAR	Product Quality Assessment Report
PR	(light path) PROxy retrieval method
PVIR	Product Validation and Intercomparison Report
QA	Quality Assurance
QC	Quality Control
RemoTeC	Retrieval algorithm developed by SRON
REQ	Requirement
RMS	Root-Mean-Square
RTM	Radiative transfer model
SCIAMACHY	SCanning Imaging Absorption spectroMeter for Atmospheric ChartographY
SCIATRAN	SCIAMACHY radiative transfer model



SRON	SRON Netherlands Institute for Space Research
SRFP	SRON's Full Physics (FP) algorithm (also referred to a RemoTeC FP)
SRPR	SRON's Proxy (PR) algorithm (also referred to a RemoTeC PR)
SWIR	Short Wava Infra Red
TANSO	Thermal And Near infrared Sensor for carbon Observation
TANSO-FTS	Fourier Transform Spectrometer on GOSAT
TANSO-FTS-2	Fourier Transform Spectrometer on GOSAT-2
TBC	To be confirmed
TBD	To be defined / to be determined
TCCON	Total Carbon Column Observing Network
TIR	Thermal Infra Red
TR	Target Requirements
TRD	Target Requirements Document
WFM-DOAS (or WFMD)	Weighting Function Modified DOAS
UoL	University of Leicester, United Kingdom
URD	User Requirements Document
WMO	World Meteorological Organization
Y2Y	Year-to-year (bias variability)



General definitions

Essential climate variable (ECV)

An ECV is a physical, chemical, or biological variable or a group of linked variables that critically contributes to the characterization of Earth's climate (Bojinski et al., 2014).

Climate data record (CDR)

The US National Research Council (NRC) defines a CDR as a time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change (National Research Council, 2004).

Fundamental climate data record (FCDR)

A fundamental climate data record (FCDR) is a CDR of calibrated and quality-controlled data designed to allow the generation of homogeneous products that are accurate and stable enough for climate monitoring.

Thematic climate data record (TCDR)

A thematic climate data record (TCDR) is a long time series of an essential climate variable (ECV) (Werscheck, 2015).

Intermediate climate data record (ICDR)

An intermediate climate data record (ICDR) is a TCDR which undergoes regular and consistent updates (Werscheck, 2015), for example because it is being generated by a satellite sensor in operation.

Satellite data processing levels

The NASA Earth Observing System (EOS) distinguishes six processing levels of satellite data, ranging from Level 0 (L0) to Level 4 (L4) as follows (Parkinson et al., 2006).

- L0 Unprocessed instrument data
- L1A Unprocessed instrument data alongside ancillary information
- L1B Data processed to sensor units (geo-located calibrated spectral radiance and solar irradiance)
- L2 Derived geophysical variables (e.g., XCO₂) over one orbit
- L3 Geophysical variables averaged in time and mapped on a global longitude/latitude horizontal grid
- L4 Model output derived by assimilation of observations, or variables derived from multiple measurements (or both)



The C3S GHG data products include the following types of data:

Level 2 data:

- Individual sensor and multi-sensor merged CO₂ and CH₄ retrievals for each (quality flagged) satellite ground-pixel

Level 3 data:

- Gridded monthly averages (5° x 5°) covering the globe in Obs4MIPs format



Table of Contents

History of modifications	4
List of datasets covered by this document	5
Related documents	6
Acronyms	7
General definitions	10
Scope of the document	14
Executive summary	17
1. Instruments	19
1.1 Instruments for XCO₂ and/or XCH₄ retrievals	19
1.1.1 SCIAMACHY onboard ENVISAT	20
1.1.2 TANSO-FTS onboard GOSAT and TANSO-FTS-2 on GOSAT-2	20
1.1.3 OCO-2	20
1.2 Instruments for mid-tropospheric mixing ratios of CO₂ and CH₄	21
1.2.1 AIRS	21
1.2.2 IASI	22
2. Inputs and auxiliary data	22
3. Algorithms	23
3.1 Algorithms for products CO₂_GOS_OCFP, CH₄_GOS_OCFP and CH₄_GOS_OCPR (ANNEX A)	23
3.2 Algorithms for products CO₂_GO₂_SRFP and CH₄_GO₂_SRFP (ANNEX B)	23
3.3 Algorithm for product CH₄_GO₂_SRPR (ANNEX C)	23
3.4 Algorithms for XCO₂_EMMA, XCH₄_EMMA, XCO₂_OBS4MIPS, XCH₄_OBS4MIPS (ANNEX D)	23
3.5 Algorithms for CO₂ and CH₄ IASI and AIRS products (ANNEX E)	24
4. Output data	25
5. Acknowledgement	29
6. List of ANNEXes	30
6.1 ANNEX A: ATBD for products CO₂_GOS_OCFP, CH₄_GOS_OCFP and CH₄_OCPR	30
6.2 ANNEX B: ATBD for products CO₂_GO₂_SRFP and CH₄_GO₂_SRFP	30
6.3 ANNEX C: ATBD for product CH₄_GO₂_SRPR	30
6.4 ANNEX D: ATBD for XCO₂_EMMA, XCH₄_EMMA, XCO₂_OBS4MIPS, XCH₄_OBS4MIPS	30



6.5 ANNEX E: ATBD for IASI and AIRS CO₂ and CH₄ products	30
References	31



Scope of the document

This document is the Algorithm Theoretical Basis Document (ATBD) for the Copernicus Climate Change Service (C3S, <https://climate.copernicus.eu/>) component as covered by the greenhouse gas (GHG) activities of project C3S2_312a_Lot2 led by DLR, Germany (the follow-on project of projects C3S_312b_Lot2, led by DLR, and project C3S_312a_Lot6, led by University of Bremen, Germany), in the following referred to as C3S/GHG project or simply as project.

Within this C3S/GHG project, satellite-derived atmospheric carbon dioxide (CO₂) and methane (CH₄) Essential Climate Variable (ECV) data products have been generated and provided to ECMWF for inclusion into the Copernicus Climate Data Store (CDS) from which users can access these data products and the corresponding documentation.

The C3S/GHG satellite-derived data products are:

- Column-averaged dry-air mixing ratios (mole fractions) of CO₂ and CH₄, denoted XCO₂ (in parts per million, ppm) and XCH₄ (in parts per billion, ppb), respectively.
- Mid/upper tropospheric mixing ratios of CO₂ (in ppm) and CH₄ (in ppb).

An overview about the products is given in Table 1 for the CO₂ products and in Table 2 for the CH₄ products.

Requirements on data quality are formulated in the corresponding Target Requirement Document (TRD) (D4).

The main purpose of this document is to describe the retrieval algorithms, which are used to generate the satellite-derived CO₂ and CH₄ greenhouse gas (GHG) ECV data products. Specifically, this document is the main ATBD providing “only” an overview of all products and their underlying retrieval algorithms. Details on each algorithm, or group of similar algorithms, are described in a set of Annexes to this document (see Sect. 6 List of ANNEXES).

For an overview of the merged Level 2 data products XCO₂_EMMA and XCH₄_EMMA and of the merged Level 3 data products XCO₂_OBS4MIPS and XCH₄_OBS4MIPS see also Reuter et al., 2020.



Table 1: Overview CO₂ products. “CRD#” indicates the Climate Data Record (CDR) Number. Level 2 (L2) products contains information for each individual satellite footprint (ground pixel) whereas Level 3 (L3) products are gridded /averaged spatially and temporally.

Product ID (Level)	Version	CDR#	Temporal coverage	Comments
CO2_GOS_OCFP (L2)	7.3	7	04.2009 – 12.2022	XCO ₂ from GOSAT as retrieved with Univ. Bremen/Leicester OCFP algorithm.
CO2_GO2_SRF (L2)	2.0.0	7	02.2019 – 12.2022	XCO ₂ from GOSAT-2 as retrieved with SRON’s SRF (RemoTeC) algorithm.
XCO2_EMMA (L2)	4.5	7	01.2003 – 12.2022	Merged L2 XCO ₂ product using Univ. Bremen’s EMMA algorithm.
XCO2_OBS4MIPS (L3)	4.5	7	01.2003 – 12.2022	Merged L3 XCO ₂ product in OBS4MIPS format.
CO2_IASA_NLIS (L2)	10.1	7	07.2007 – 10.2021	Mid-tropospheric CO ₂ mixing ratios as retrieved from IASI/Metop-A using LMD’s NLIS algorithm. Data set ends in 2021 due to end of mission.
CO2_IASB_NLIS (L2)	10.1	7	02.2013 – 12.2022	Mid-tropospheric CO ₂ mixing ratios as retrieved from IASI/Metop-B using LMD’s NLIS algorithm.
CO2_IASC_NLIS (L2)	10.1	7	05.2019 – 12.2022	Mid-tropospheric CO ₂ mixing ratios as retrieved from IASI/Metop-C using LMD’s NLIS algorithm.



Table 2: Overview CH₄ products. “CRD#” indicates the Climate Data Record (CDR) Number. Level 2 (L2) products contains information for each individual satellite footprint (ground pixel) whereas Level 3 (L3) products are gridded /averaged spatially and temporally.

Product ID (Level)	Version	CDR#	Temporal coverage	Comments
CH4_GOS_OCFP (L2)	7.3	7	04.2009 – 12.2022	XCH ₄ from GOSAT as retrieved with Univ. Bremen/Leicester OCFP algorithm.
CH4_GOS_OCPR (L2)	9.0	7	04.2009 – 12.2022	XCH ₄ from GOSAT as retrieved with Univ. Bremen/Leicester OCPR algorithm.
CH4_GO2_SRF (L2)	2.0.0	7	02.2019 – 12.2022	XCH ₄ from GOSAT-2 as retrieved with SRON’s SRF (RemoTeC) algorithm.
CH4_GO2_SRPR (L2)	2.0.1	7	02.2019 – 12.2022	XCH ₄ from GOSAT-2 as retrieved with SRON’s SRPR (RemoTeC) algorithm.
XCH4_EMMA (L2)	4.5	7	01.2003 – 12.2022	Merged L2 XCH ₄ product using Univ. Bremen’s EMMA algorithm.
XCH4_OBS4MIPS (L3)	4.5	7	01.2003 – 12.2022	Merged L3 XCH ₄ product in OBS4MIPS format.
CH4_IASA_NLIS (L2)	10.2	7	07.2007 – 10.2021	Mid-tropospheric CH ₄ mixing ratios as retrieved from IASI/Metop-A using LMD’s NLIS algorithm. Data set ends in 2021 due to end of mission.
CH4_IASB_NLIS (L2)	10.2	7	02.2013 – 12.2022	Mid-tropospheric CH ₄ mixing ratios as retrieved from IASI/Metop-B using LMD’s NLIS algorithm.
CH4_IASC_NLIS (L2)	10.2	7	05.2019 – 12.2022	Mid-tropospheric CH ₄ mixing ratios as retrieved from IASI/Metop-C using LMD’s NLIS algorithm.



Executive summary

CO₂ and CH₄ are important climate-relevant atmospheric gases, so-called greenhouse gases (GHG). Because of their important role for climate, they are classified as Essential Climate Variables (ECVs). The ECV GHG as formulated by GCOS (Global Climate Observing System) is defined as follows: “Retrievals of greenhouse gases, such as CO₂ and CH₄, of sufficient quality to estimate regional sources and sinks” (GCOS-154). This definition contains already the main application of these atmospheric data products, namely to use them (in combination with appropriate modelling) to obtain (improved) information on their (primarily surface) sources and sinks.

In this document the retrieval algorithms are described, which are used to generate satellite-derived atmospheric carbon dioxide (CO₂) and methane (CH₄) Climate Data Record (CDR) data products as generated via the C3S2_312a_Lot2 project of the Copernicus Climate Change Service (C3S, <https://climate.copernicus.eu/>).

These satellite-derived greenhouse gas (GHG) data products are:

- Column-averaged dry-air mixing ratios (mole fractions) of CO₂ and CH₄, denoted XCO₂ (in parts per million, ppm) and XCH₄ (in parts per billion, ppb), respectively.
- Mid/upper tropospheric mixing ratios of CO₂ (in ppm) and CH₄ (in ppb).

The C3S GHG data products are generated - or have been generated in the past - from the satellite instruments SCIAMACHY onboard ENVISAT, TANSO-FTS/GOSAT, TANSO-FTS-2/GOSAT-2 (XCO₂ and XCH₄ products) and AIRS and IASI (mid/upper troposphere products). Products from SCIAMACHY and AIRS have been generated in pre-cursor projects and no updates are generated within this project; the corresponding GHG products are available via the Copernicus Climate Data Store (CDS, <https://cds.climate.copernicus.eu/>). Note however that SCIAMACHY products are used as input for the generation of the four merged products that are produced here: XCO2_EMMA, XCO2_OBS4MIPS, XCH4_EMMA, and XCH4_OBS4MIPS. For the products XCO2_EMMA and XCO2_OBS4MIPS also Level 2 products from NASA’s OCO-2 mission have been used as input products (see also Reuter et al., 2020).

All data products are available in NetCDF format (NetCDF-4 classic format in-line with Climate and Forecasting (CF) convention 3). All products except the two (XCO₂ and XCH₄) Level 3 Obs4MIPS format products are Level 2 products. The XCO₂ and XCH₄ Level 2 products correspond to individual satellite sensors but are also available as merged multi-sensor products (the so-called EMMA products).

The greenhouse gas (GHG) activities of this C3S project and its C3S pre-cursor projects are essentially the operational continuation of the research and development (R&D) pre-cursor projects GHG-CCI and GHG-CCI+ of ESA’s Climate Change Initiative (CCI). R&D for the GOSAT-2 products is currently an ongoing activity of the ESA GHG-CCI+ project (see <https://climate.esa.int/en/projects/ghgs/>).

The first GHG data set - Climate Data Record 1 (CDR1) - covered the time period 2003-2016 and was delivered to ECMWF in 2017. That data set and its documentation was made available via the C3S CDS in 2018. The second data set - Climate Data Record 2 (CDR2) - covered the time period 2003-2017 and was made available for the C3S CDS in 2018. This document is an update of the ATBD for the latest CDR data set CDR7 covering the time period 2002-2022.



The algorithms which are used to retrieve XCO_2 and/or XCH_4 from SCIAMACHY/ENVISAT, TANSO-FTS/GOSAT/GOSAT-2 and OCO-2 are based on radiative transfer modelling of the observed radiance spectra. Using Optimal Estimation (OE) or Least-Squares retrieval methods, parameters called state vector elements (or fit parameters) are iteratively adjusted until a good match is obtained between the modelled and the observed radiance spectra. Among these state vector elements are those elements which permit to compute the desired parameters XCO_2 and XCH_4 . These state vector elements are parameters describing the CO_2 and CH_4 vertical profile or directly correspond to their vertical column. Other state vector elements consider effects which are also required for accurate modelling of the observed spectra such as parameters related to surface reflection, atmospheric scattering (aerosols, clouds), water vapour and temperature vertical profiles and surface pressure. Output of these algorithms are not only the quantities XCO_2 and XCH_4 but also their uncertainty and their altitude sensitivity (averaging kernels) as well as a quality flag, which indicated if the retrieval is considered reliable or not. The quality flag reflects the quality of the spectral fit but is also determined by a number of other aspects such as the values of certain state vector elements (or combinations of them). These algorithms are typically relatively slow as line absorption as well as multiple scattering needs to be considered for the radiative transfer simulations, which cover a quite large spectral region. In contrast, the algorithm used to retrieve mid/upper tropospheric CO_2 and CH_4 mixing ratios from the IASI instruments on the Metop satellite series is very fast as it is based on the neuronal network method.

This document is structured as follows: In Sect. 1 an overview of the satellites instruments is provided. Sect. 2 addresses input data and auxiliary data as used by the retrieval algorithms. The main section is Sect. 3, where the retrieval algorithms are described. Output data are addressed in Sect. 4. An acknowledgment is given in Sect. 5. Note that this document is the MAIN ATBD document providing only a very short overview about the retrieval algorithms. Details on each algorithm are provided in separate Annexes (see Sect. 6):

- **ANNEX A:** ATBD for XCO_2 and XCH_4 Level 2 products $\text{CO}_2_GOS_OCFP$, $\text{CH}_4_GOS_OCFP$ and $\text{CH}_4_GOS_OCPR$ retrieved from GOSAT using University of Leicester's "full physics" (FP) and "proxy" (PR) retrieval algorithms
- **ANNEX B:** ATBD for XCO_2 and XCH_4 Level 2 products $\text{CO}_2_GO2_SRFP$ and $\text{CH}_4_GO2_SRFP$ retrieved using SRON's FP retrieval algorithm from GOSAT-2
- **ANNEX C:** ATBD for XCH_4 Level 2 product $\text{CH}_4_GO2_SRPR$ retrieved using SRON's PR retrieval algorithm from GOSAT-2
- **ANNEX D:** ATBD for merged multi-sensor / multi-algorithms Level 2 and Level 3 products XCO_2_EMMA , XCH_4_EMMA , $\text{XCO}_2_OBS4MIPS$ and $\text{XCH}_4_OBS4MIPS$ as generated using University of Bremen's algorithms
- **ANNEX E:** ATBD for IASI CO_2 and CH_4 Level 2 mid/upper troposphere products generated at LMD (includes also information on AIRS CO_2 mid-tropospheric products generated in a previous project)



1. Instruments

1.1 Instruments for XCO₂ and/or XCH₄ retrievals

Satellite radiance observations in the Near Infrared / Short Wave Infrared (NIR/SWIR) spectral region in nadir (downward looking) observation viewing mode are sensitive to atmospheric CO₂ and CH₄ concentration changes with good sensitivity down to the Earth's surface (because solar radiation reflected at the Earth's surface is observed). These measurements permit to obtain "total column information" but do not permit to obtain (detailed) information on the vertical profiles of CO₂ and CH₄. The CO₂ and CH₄ products derived from these satellites are column-averaged dry-air mixing ratios (more precisely: mole fractions) of CO₂ and CH₄ denoted XCO₂ (e.g., in ppm) and XCH₄ (e.g., in ppb).

In the following, several satellite instruments are briefly described which are used or can be used to generate XCO₂ and/or XCH₄ data products. Note that details on instruments and corresponding satellites are provided in the relevant Annex (see Sect. 6).

Currently data from four of these instruments – SCIAMACHY/ENVISAT, TANSO-FTS/GOSAT, TANSO-FTS-2/GOSAT-2 and OCO-2 - have been used to generate the XCO₂ and XCH₄ data products described in this document (see Table 3 and details provided below in Sect. 1.1.1 to Sect. 1.1.3). Data products from additional sensors may be added in the future.

Table 3 – Overview of the key characteristics of the four satellite sensors used to generate the XCO₂ and XCH₄ data products. All sensors perform nadir observations of reflected solar radiation in the NIR/SWIR spectral region at moderate to high spectral resolution.

Satellite	Sensor	Mission Duration	Spatial resolution	Comments
ENVISAT	SCIAMACHY	01.2002 - 04.2012	60 km x 30 km	Global coverage nadir mode observations after 6 days
GOSAT	TANSO-FTS	01.2009 - ongoing	10.5 km (circle)	Global coverage with 3 days repeat cycle but large gaps due non-consecutive sampling
GOSAT-2	TANSO-FTS-2	10.2018 - ongoing	10.5 km (circle)	Similar as GOSAT but with optimized scan pattern
OCO-2	OCO-2	07.2014 - ongoing	1.3 km x 2.3 km	Global with 16 days repeat cycle but large gaps due to narrow swath (10 km)



1.1.1 SCIAMACHY onboard ENVISAT

SCIAMACHY (SCanning Imaging Absorption spectroMeter for Atmospheric ChartographY) was a spectrometer on ESA's ENVISAT satellite (2002-2012). SCIAMACHY (Burrows et al., 2005; Bovensmann et al., 1999) covers the spectral region from the ultra-violet to the SWIR spectral region (240 nm - 2380 nm) at moderate spectral resolution (0.2 nm - 1.5 nm) and observes the Earth's atmosphere in various viewing geometries (nadir, limb and solar and lunar occultation). For a good general overview on SCIAMACHY see <https://www.iup.uni-bremen.de/sciamachy/> and <https://en.wikipedia.org/wiki/SCIAMACHY>. SCIAMACHY permits the retrieval of XCO₂ (e.g., Reuter et al., 2011; Schneising et al., 2011) and XCH₄ (e.g., Schneising et al., 2011; Frankenberg et al., 2011) from the appropriate spectral regions in the SWIR (around 1.6 µm) and the NIR (O₂ A-band at 760 nm used to obtain the dry-air column using the known dry-air mixing ratio of atmospheric oxygen). The ground pixel size is typically 30 km along track times 60 km across track and the swath width is about 960 km. There are no across-track gaps between the ground pixels but there are gaps along-track as SCIAMACHY operates only part of the time (approx. 50%) in nadir observation mode.

1.1.2 TANSO-FTS onboard GOSAT and TANSO-FTS-2 on GOSAT-2

TANSO-FTS is a Fourier-Transform-Spectrometer (FTS) onboard the Japanese GOSAT satellite (Kuze et al., 2009, 2014, 2016). The Greenhouse Gases Observing Satellite "IBUKI" (GOSAT) is the world's first spacecraft in orbit dedicated to measure the concentrations of carbon dioxide and methane from space. The spacecraft was launched successfully on January 23, 2009, and has been operating properly since then. GOSAT covers the relevant CO₂, CH₄ and O₂ absorption bands in the NIR and SWIR spectral region as needed for accurate XCO₂ and XCH₄ retrieval (in addition GOSAT also covers a large part of the Thermal Infrared (TIR) spectral region). The spectral resolution of TANSO-FTS is much higher compared to SCIAMACHY and the ground pixels are smaller (10 km compared to several 10 km for SCIAMACHY). However, in contrast to SCIAMACHY, the GOSAT scan pattern consists of non-consecutive individual ground pixels, i.e., the scan pattern is not gap-free. For a good general overview about GOSAT see also <http://www.gosat.nies.go.jp/en/>.

GOSAT-2 (Suto et al., 2021) is the follow-on satellite to GOSAT and very similar compared to GOSAT. GOSAT-2 was successfully launched on 29 October 2018. GOSAT-2 XCO₂ and XCH₄ retrievals are now also included in the C3S GHG CDR.

Concerning XCO₂ and XCH₄ retrieval from GOSAT and GOSAT-2 see also Noël et al., 2021 and 2022.

1.1.3 OCO-2

NASA's Orbiting Carbon Observatory 2 (OCO-2) mission (Crisp et al., 2004; Boesch et al., 2011) has been successfully launched in July 2014. The OCO-2 Project primary science objective is to collect the first space-based measurements of atmospheric carbon dioxide with the precision, resolution and coverage needed to characterize its sources and sinks and quantify their variability over the seasonal cycle. During its two-year mission, OCO-2 will fly in a sun-synchronous, near-polar orbit



with a group of Earth-orbiting satellites with synergistic science objectives whose ascending node crosses the equator near 13:30 hours Mean Local Time (MLT). Near-global coverage of the sunlit portion of Earth is provided in this orbit over a 16-day (233-revolution) repeat cycle. OCO-2's single instrument incorporates three high-resolution grating spectrometers, designed to measure the near-infrared absorption of reflected sunlight by carbon dioxide and molecular oxygen. OCO-2 covers similar spectral bands as SCIAMACHY and GOSAT but OCO-2 has much smaller ground pixels (km scale) but the swath width is much smaller (approx. 10 km) compared to SCIAMACHY. OCO-2 delivers XCO₂ but not XCH₄. Details on OCO-2 are also given on <https://oco.jpl.nasa.gov/>.

1.2 Instruments for mid-tropospheric mixing ratios of CO₂ and CH₄

Satellite radiance observations in the thermal infrared (TIR) spectral region in nadir (downward looking) observation viewing mode are sensitive to atmospheric CO₂ and CH₄ mixing ratio changes in the mid and upper tropospheric region. They can thus be interpreted in terms of integrated mid-tropospheric columns, with typical sensitivity between 5 and 12 km.

Mid-tropospheric columns of CO₂ can be retrieved from hyperspectral infrared sounders such as AIRS and IASI (Chédin et al., 2003; Crevoisier et al., 2003) using non-linear inference scheme (Crevoisier et al., 2009a). Products can be validated using aircraft measurements, mostly from the Comprehensive Observation Network for TRace gases by AirLiner (CONTRAIL) program (Machida et al., 2008; Matsueda et al. 2008).

Mid-tropospheric columns of CH₄ can be retrieved from the hyperspectral infrared sounder IASI (Crevoisier et al., 2003, 2013) using non-linear inference scheme (Crevoisier et al., 2009b). Products can be validated using aircraft measurements, from the Comprehensive Observation Network for TRace gases by AirLiner (CONTRAIL) program (Machida et al., 2008; Matsueda et al. 2008) and the HIPER Pole-to-Pole Observations (HIPPO) project (Wofsy et al., 2012), as well as from balloon measurements from AirCores (Membrive et al., 2016).

In the following, the 2 hyperspectral infrared sounders AIRS and IASI are briefly described.

1.2.1 AIRS

The Atmospheric Infrared Sounder (AIRS) is a polar orbiting nadir-viewing high-resolution infrared sounder operating in a cross-track-scanning mode. It was launched on-board the EOS Aqua satellite in May 2002, with two operational microwave sounders, AMSU and HSB, and is operational since September 2002. It is a high-spectral resolution, grating multispectral infrared sounder with 2378 channels. Its spectral domain ranges from 650 cm⁻¹ to 2665 cm⁻¹ (15.4 μm and 3.8 μm), with a spectral resolving power of 1200 (i.e., a spectral resolution ranging from 0.5 cm⁻¹ to 2 cm⁻¹). This domain is divided into three spectral bands, from 650 to 1135 cm⁻¹, from 1215 to 1615 cm⁻¹ and from 2180 to 2665 cm⁻¹. AIRS cross-track scanning is 1650 km and covers 70% of the earth every day. The instantaneous field of view (IFOV) is sampled by 3×3 circular pixels whose ground resolution is 13 km at nadir. Measurements from the three instruments are analyzed jointly to filter



out the effects of clouds from the IR data in order to derive clear-column air-temperature profiles and surface temperatures with high vertical resolution and accuracy (1 K per 1 km layer in the troposphere).

1.2.2 IASI

The Infrared Atmospheric Sounding Interferometer (IASI) is a high resolution Fourier Transform Spectrometer based on a Michelson Interferometer coupled to an integrated imaging system that measures infrared radiation emitted from the Earth. Developed by the Center National d'Etudes Spatiales (CNES) in collaboration with the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), IASI was launched in October 2006 on-board the polar orbiting Meteorological Operational Platform (Metop-A), in September 2012 on-board Metop-B, and in November 2018 onboard Metop-C. IASI provides 8461 spectral samples, ranging from 645 cm^{-1} to 2760 cm^{-1} ($15.5\text{ }\mu\text{m}$ and $3.6\text{ }\mu\text{m}$), with a spectral sampling of 0.25 cm^{-1} , and a spectral resolution of 0.5 cm^{-1} after apodisation, i.e., after application of a method to reduce the spectral resolution ('Level 1c' spectra). IASI is an across track scanning system, whose swath width is of 2200 km, allowing global coverage twice a day. The IFOV is sampled by 2×2 circular pixels whose ground resolution is 12 km at nadir. IASI has demonstrated the possibility to retrieve or detect several chemistry and climate variables from hyperspectral infrared observation: for instance, water vapour (H_2O), carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), ozone (O_3), sulphur dioxide (SO_2), hydrogen sulphide (H_2S), ammonia (NH_3), nitric acid (HNO_3), volatile organic compounds (VOCs) and aerosols (Hilton et al., 2012; Clarisse et al., 2011) on regional and global scales. IASI enables the monitoring of key gases for climate and atmospheric chemistry in near real time and has also highlighted the benefit of high-performance infrared sounders for numerical weather prevision (NWP) applications.

2. Inputs and auxiliary data

Details on input and auxiliary data are given in specific Annexes (see Sect. 6.).



3. Algorithms

3.1 Algorithms for products CO2_GOS_OCFP, CH4_GOS_OCFP and CH4_GOS_OCPR (ANNEX A)

The products CO2_GOS_OCFP, CH4_GOS_OCFP and CH4_GOS_OCPR are XCO₂ and XCH₄ Level 2 products as retrieved from GOSAT using retrieval algorithms developed at the University of Leicester, UK.

For details see the separate ATBD provided as ANNEX A.

3.2 Algorithms for products CO2_GO2_SRFP and CH4_GO2_SRFP (ANNEX B)

The products CO2_GO2_SRFP and CH4_GO2_SRFP are XCO₂ and XCH₄ Level 2 products as retrieved from GOSAT-2 using “Full Physics” (FP) algorithms developed at SRON, The Netherlands.

For details see the separate ATBD provided as ANNEX B.

3.3 Algorithm for product CH4_GO2_SRPR (ANNEX C)

The product CH4_GO2_SRPR is a XCH₄ Level 2 product as retrieved from GOSAT-2 using a (light path) “Proxy” (PR) algorithm developed at SRON, The Netherlands.

For details see the separate ATBD provided as ANNEX C.

3.4 Algorithms for XCO2_EMMA, XCH4_EMMA, XCO2_OBS4MIPS, XCH4_OBS4MIPS (ANNEX D)

The products XCO₂_EMMA and XCH₄_EMMA are merged multi-sensor XCO₂ and XCH₄ Level 2 products generated using the Ensemble Median Algorithm (EMMA, Reuter et al., 2013) developed at University of Bremen, Germany. The OBS4MIPS product are derived from the EMMA products (via “gridding”). They have a spatial resolution of 5°x5° and monthly time resolution.

For details see the separate ATBD provided as ANNEX D.



3.5 Algorithms for CO₂ and CH₄ IASI and AIRS products (ANNEX E)

The IASI products are mid-tropospheric CO₂ and CH₄ mixing ratios and the AIRS product is a mid-tropospheric CO₂ mixing ratio product. These products are retrieved using algorithms developed at LMD/CNRS, France.

For details see the separate ATBD provided as ANNEX E.



4. Output data

The output data products are (see also Buchwitz et al., 2013b, 2017, 2017b):

- Column-averaged dry-air mixing ratios (mole fractions) of CO₂ and CH₄, denoted XCO₂ (in parts per million, ppm) and XCH₄ (in parts per billion, ppb).
- Mid/upper tropospheric mixing ratios of CO₂ and CH₄.

Carbon dioxide and methane are important atmospheric greenhouse gases (e.g., IPCC 2013) but despite their importance our knowledge on their various and variable natural and anthropogenic sources and sinks has significant gaps (e.g., IPCC 2013; Ciais et al., 2014; 2015; Kirschke et al., 2013; Nisbet et al., 2014, and references given therein). A purpose of the satellite data products described in this document is to contribute to enhancing our knowledge on the CO₂ and CH₄ sources and sinks (via appropriate (inverse) modelling).

Carbon dioxide and methane are so-called Essential Climate Variables (ECVs) and the need to monitor them has been clearly identified including the definition of key requirements (e.g., GCOS-154, GCOS-200). In recent years several satellite-derived ECV data products have been generated in particular in the framework of the Climate Change Initiative (CCI) of ESA (e.g., Hollmann et al., 2013) including CO₂ and CH₄ (e.g., Buchwitz et al., 2013a, 2016, 2017, 2017b).

These satellite-derived CO₂ and CH₄ data products are used for a number of (primarily scientific) applications, e.g.,

- to improve our knowledge on the various natural and anthropogenic (surface) sources and sinks of these important greenhouse gases (GHG) (see, e.g., Alexe et al., 2015; Chevallier et al., 2014, 2016a, 2016b; Cressot et al., 2014; Detmers et al., 2015; Guerlet et al., 2013; Houweling et al., 2015; McNorton et al., 2016; Pandey et al., 2016; Reuter et al., 2014b, 2017; Schneising et al., 2014b; Turner et al., 2015, 2016, and references given therein)
- to monitor the global distribution of CO₂ and CH₄ (e.g., Buchwitz et al., 2007, 2016, 2017b; Schneising et al., 2011; Frankenberg et al., 2011; Massart et al., 2016)
- to improve our knowledge on emission ratios, e.g., for biomass burning (e.g., Ross et al., 2013; Parker et al., 2016)
- for comparisons with (chemistry) climate models (e.g., Shindell et al., 2013; Hayman et al., 2014; Lauer et al., 2017) and other models (e.g., Schneising et al., 2014a; Parker et al., 2016)

The output data consist for each Level 2 product of one daily NetCDF file (NetCDF-4 classic format in-line with Climate and Forecasting (CF) convention 3). These files contain for each single satellite footprint (ground pixel) the main parameter (e.g., XCO₂ or XCH₄ or mid-tropospheric CO₂ or CH₄), its uncertainty, its averaging kernel and its *a priori* profile in addition to other information (most notable geolocation and time information: latitude, longitude, time). In addition, two Level 3 products are generated: one for XCO₂ and one for XCH₄. Each product is stored in a single file covering the entire time series, i.e., there is one file for XCO₂ and one file for XCH₄. For details on the output format please see the corresponding Product User Guide and Specification (PUGS) document [D5].



The following tables (Table 4 - Table 6) provide an overview of the CO₂ and CH₄ data products.

Table 4 - Overview XCO₂ data products. Information is listed for the last two CDRs. Availability refers to the (planned) availability of the data product via the Copernicus Climate Data Store (CDS). “Temporal coverage” refers to the start and the end date of the data product.

Product ID	Level	Sensor(s)	CDR number: (Planned) Availability: Temporal coverage	Comments
CO2_GOS_OCFP	2	GOSAT	CDR 6: Dec. 2022: 2009-2021 CDR 7: Dec. 2023: 2009-2022	Universities Bremen/Leicester “Full Physics” (FP) algorithm
CO2_GO2_SRF	2	GOSAT-2	CDR 6: Dec. 2022: 2019-2021 CDR 7: Dec. 2023: 2019-2022	SRON’s “Full Physics” (FP) algorithm
XCO2_EMMA	2	Merged SCIAMACHY, GOSAT, OCO-2	CDR 6: Dec. 2022: 2003-2021 CDR 7: Dec. 2023: 2003-2022	Univ. Bremen’s Level 2 merging algorithm
XCO2_OBS4MIPS	3	Merged SCIAMACHY, GOSAT, OCO-2	CDR 6: Dec. 2022: 2003-2021 CDR 7: Dec. 2023: 2003-2022	Gridded EMMA product in Obs4MIPs format



Table 5 - Overview XCH₄ data products. Information is listed for the last two CDRs. Availability refers to the (planned) availability of the data product via the Copernicus Climate Data Store (CDS). “Temporal coverage” refers to the start and the end date of the data product.

Product ID	Level	Sensor(s)	CDR number: (Planned) Availability: Temporal coverage	Comments
CH4_GOS_OCPR	2	GOSAT	CDR 6: Dec. 2022: 2009-2021 CDR 7: Dec. 2023: 2009-2022	Universities Bremen/Leicester “Proxy” (PR) algorithm
CH4_GOS_OCFP	2	GOSAT	CDR 6: Dec. 2022: 2009-2021 CDR 7: Dec. 2023: 2009-2022	Universities Bremen/Leicester “Full Physics” (FP) algorithm
CH4_GO2_SRPR	2	GOSAT-2	CDR 6: Dec. 2022: 2019-2021 CDR 7: Dec. 2023: 2019-2022	SRON’s “Proxy” (PR) algorithm
CH4_GO2_SRFp	2	GOSAT-2	CDR 6: Dec. 2022: 2019-2021 CDR 7: Dec. 2023: 2019-2022	SRON’s “Full Physics” (FP) algorithm
XCH4_EMMA	2	Merged SCIAMACHY & GOSAT	CDR 6: Dec. 2022: 2003-2021 CDR 7: Dec. 2023: 2003-2022	Univ. Bremen’s Level 2 merging algorithm
XCH4_OBS4MIPS	3	Merged SCIAMACHY & GOSAT	CDR 6: Dec. 2022: 2003-2021 CDR 7: Dec. 2023: 2003-2022	Gridded EMMA product in Obs4MIPs format



Table 6: Overview mid/upper troposphere CO₂ and CH₄ data products. Information is listed for the last two CDRs. Availability refers to the (planned) availability of the data product via the Copernicus Climate Data Store (CDS). “Temporal coverage” refers to the start and the end date of the data product.

Product ID	Level	Sensor(s)	CDR number: (Planned) Availability: Temporal coverage	Comments
CO2_IASA_NLIS	2	IASI / Metop-A	CDR 6: Dec. 2022: 2007-08.2021 CDR 7: Dec. 2022: 2007-10.2021	Improved in this project
CH4_IASA_NLIS	2	IASI / Metop-A	CDR 6: Dec. 2022: 2007-08.2021 CDR 7: Dec. 2022: 2007-10.2021	Improved in this project
CO2_IASB_NLIS	2	IASI / Metop-B	CDR 6: Dec. 2022: 2013-2021 CDR 7: Dec. 2023: 02.2013-12.2022	Improved in this project
CH4_IASB_NLIS	2	IASI / Metop-B	CDR 6: Dec. 2022: 2013-2021 CDR 7: Dec. 2023: 02.2013-12.2022	Improved in this project
CO2_IASC_NLIS	2	IASI / Metop-C	CDR 7: Dec. 2023: 05.2019-12.2022	New in this project
CH4_IASC_NLIS	2	IASI / Metop-C	CDR 7: Dec. 2023: 05.2019-12.2022	New in this project



5. Acknowledgement

We acknowledge previous funding by the European Space Agency (ESA) via Climate Change Initiative (CCI) project GHG-CCI. This funding significantly enhanced the quality of the retrieval algorithms and related documentation. This resulted in more mature data products as needed for an operational project such as the Copernicus Climate Change Service (C3S). We also acknowledge the availability of GOSAT and GOSAT-2 data products via the ESA GOSAT Third Party Mission (TPM) archive.

We are also very grateful to the GOSAT/GOSAT-2 teams in Japan comprising the Japan Aerospace Exploration Agency (JAXA), the National Institute for Environmental Studies (NIES), and the Ministry of the Environment (MOE) for providing access to the GOSAT and GOSAT-2 Level 1 and Level 2 data products.

We also acknowledge the availability of OCO-2 Level 1 and Level 2 (XCO₂) data products from NASA, which have been used for the generation on the XCO₂_EMMA and XCO₂_OBS4MIPS products. These products also include OCO-2 XCO₂ retrieved at Univ. Bremen with the FOCAL algorithm. The FOCAL activities would not have been possible without funding from University of Bremen, from the EU H2020 projects CHE (grant agreement ID: 776186) and VERIFY (Grant agreement ID: 776810), from ESA via project GHG-CCI+ and from EUMETSAT project FOCAL-CO2M.

Finally, yet importantly we acknowledge the availability of TCCON data via the TCCON data archive (<https://tccondata.org/>).



6. List of ANNEXes

The ANNEXes to this main document are the following ANNEXes A – E:

6.1 ANNEX A: ATBD for products CO₂_GOS_OCFP, CH₄_GOS_OCFP and CH₄_OCPR

Describes algorithms for GOSAT XCO₂ and XCH₄ Level 2 products generated by University of Leicester, UK, in cooperation with University of Bremen, Germany.

6.2 ANNEX B: ATBD for products CO₂_GO₂_SRFP and CH₄_GO₂_SRFP

Describes algorithms for GOSAT-2 XCO₂ and XCH₄ Full Physics (FP) Level 2 products generated by SRON, The Netherlands.

6.3 ANNEX C: ATBD for product CH₄_GO₂_SRPR

Describes the algorithm for GOSAT-2 XCH₄ Proxy (PR) Level 2 product generated by SRON, The Netherlands.

6.4 ANNEX D: ATBD for XCO₂_EMMA, XCH₄_EMMA, XCO₂_OBS4MIPS, XCH₄_OBS4MIPS

Describes algorithms for multi-sensor merged XCO₂ and XCH₄ Level 2 (“EMMA”) products and gridded Level 3 (“OBS4MIPS”) products (as derived from the EMMA products) generated by University of Bremen, Germany.

6.5 ANNEX E: ATBD for IASI and AIRS CO₂ and CH₄ products

Describes algorithms for mid-tropospheric CO₂ and CH₄ products from the IASI instrument series and from AIRS generated by LMD/CNRS, France.

These ANNEXes and the corresponding data products are / will be available via the Copernicus Climate Data Store (CDS):

<https://cds.climate.copernicus.eu/#!/home>

See also Copernicus Climate Change Service (C3S):

<https://climate.copernicus.eu/>

pdf versions of all documents (including previous versions) are (also) available from

https://www.iup.uni-bremen.de/carbon_ghg/cg_data.html#C3S_GHG



References

- Alexe et al., 2015:** Alexe, M., P. Bergamaschi, A. Segers, R. Detmers, A. Butz, O. Hasekamp, S. Guerlet, R. Parker, H. Boesch, C. Frankenberg, R. A. Scheepmaker, E. Dlugokencky, C. Sweeney, S. C. Wofsy, and E. A. Kort, Inverse modeling of CH₄ emissions for 2010–2011 using different satellite retrieval products from GOSAT and SCIAMACHY, *Atmos. Chem. Phys.*, 15, 113–133, doi:10.5194/acp-15-113-2015, 2015.
- ATBD GHG, 2023:** Buchwitz, M., Barr, A., Boesch, H., Borsdorff, T., Crevoisier, C., Di Noia, A., Hasekamp, O. P., Landgraf, J., Meilhac, N., Parker, R., Reuter, M., Schneising-Weigel, O.: Algorithm Theoretical Basis Document (ATBD) – Main document for Greenhouse Gas (GHG: CO₂ & CH₄) data set CDR6 (01.2003-12.2021), C3S project C3S2_312a_Lot2_DLR, v6.2, 2023. Link: https://www.iup.uni-bremen.de/carbon_ghg/docs/C3S/CDR6_2003-2021/C3S2_312a_Lot2_D-WP1_ATBD-2022-GHG_MAIN_v6.2.pdf
- Boesch et al., 2011:** Boesch, H., D. Baker, B. Connor, D. Crisp, and C. Miller, Global characterization of CO₂ column retrievals from shortwave-infrared satellite observations of the Orbiting Carbon Observatory-2 mission, *Remote Sensing*, 3 (2), 270-304, 2011.
- Bojinski et al., 2014:** Bojinski, S., M. Verstraete, T. C. Peterson, C. Richter, A. Simmons and M. Zemp, The concept of essential climate variables in support of climate research, applications and policy, *Bulletin of the American Meteorological Society (BAMS)*, 1431-1443, September 2014. http://www.wmo.int/pages/prog/gcos/documents/bams_ECV_article.pdf
- Bovensmann et al., 1999:** Bovensmann, H., Burrows, J. P., Buchwitz, M., Frerick, J., Noël, S., Rozanov, V. V., Chance, K. V., Goede, A. H. P. (1999), SCIAMACHY - Mission objectives and measurement modes, *J. Atmos. Sci.*, 56 (2), 127-150, 1999.
- Buchwitz et al., 2000:** Buchwitz, M., Rozanov, V. V., and Burrows, J. P.: A near-infrared optimized DOAS method for the fast global retrieval of atmospheric CH₄, CO, CO₂, H₂O, and N₂O total column amounts from SCIAMACHY Envisat-1 nadir radiances, *J. Geophys. Res.* 105, 15,231-15,245, 2000.
- Buchwitz et al., 2005:** Buchwitz, M., R. de Beek, J. P. Burrows, H. Bovensmann, T. Warneke, J. Notholt, J. F. Meirink, A. P. H. Goede, P. Bergamaschi, S. Körner, M. Heimann, and A. Schulz, Atmospheric methane and carbon dioxide from SCIAMACHY satellite data: Initial comparison with chemistry and transport models, *Atmos. Chem. Phys.*, 5, 941-962, 2005.
- Buchwitz et al., 2007:** Buchwitz, M., O. Schneising, J. P. Burrows, H. Bovensmann, M. Reuter, J. Notholt, First direct observation of the atmospheric CO₂ year-to-year increase from space, *Atmos. Chem. Phys.*, 7, 4249-4256, 2007.
- Buchwitz et al., 2013a:** Buchwitz, M., M. Reuter, O. Schneising, H. Boesch, S. Guerlet, B. Dils, I. Aben, R. Armante, P. Bergamaschi, T. Blumenstock, H. Bovensmann, D. Brunner, B. Buchmann, J. P. Burrows, A. Butz, A. Chédin, F. Chevallier, C. D. Crevoisier, N. M. Deutscher, C. Frankenberg, F. Hase, O. P. Hasekamp, J. Heymann, T. Kaminski, A. Laeng, G. Lichtenberg, M. De Mazière, S. Noël, J. Notholt, J. Orphal, C. Popp, R. Parker, M. Scholze, R. Sussmann, G. P. Stiller, T. Warneke, C. Zehner, A. Bril, D. Crisp, D. W. T. Griffith, A. Kuze, C. O'Dell, S. Oshchepkov, V. Sherlock, H. Suto, P. Wennberg, D. Wunch, T. Yokota, Y. Yoshida, The Greenhouse Gas Climate Change Initiative (GHG-



CCI): comparison and quality assessment of near-surface-sensitive satellite-derived CO₂ and CH₄ global data sets, *Remote Sensing of Environment*, doi:10.1016/j.rse.2013.04.024, 2013.

Buchwitz et al., 2013b: Buchwitz, M., Reuter, M., Bovensmann, H., Pillai, D., Heymann, J., Schneising, O., Rozanov, V., Krings, T., Burrows, J. P., Boesch, H., Gerbig, C., Meijer, Y., and Loesch, A.: Carbon Monitoring Satellite (CarbonSat): assessment of atmospheric CO₂ and CH₄ retrieval errors by error parameterization, *Atmos. Meas. Tech.*, 6, 3477–3500, 2013.

Buchwitz et al., 2015: Buchwitz, M., Reuter, M., Schneising, O., Boesch, H., Guerlet, S., Dils, B., Aben, I., Armante, R., Bergamaschi, P., Blumenstock, T., Bovensmann, H., Brunner, D., Buchmann, B., Burrows, J.P., Butz, A., Chédin, A., Chevallier, F., Crevoisier, C.D., Deutscher, N.M., Frankenberg, C., Hase, F., Hasekamp, O.P., Heymann, J., Kaminski, T., Laeng, A., Lichtenberg, G., De Mazière, M., Noël, S., Notholt, J., Orphal, J., Popp, C., Parker, R., Scholze, M., Sussmann, R., Stiller, G.P., Warneke, T., Zehner, C., Bril, A., Crisp, D., Griffith, D.W.T., Kuze, A., O'Dell, C., Oshchepkov, S., Sherlock, V., Suto, H., Wennberg, P., Wunch, D., Yokota, T., Yoshida, Y., The Greenhouse Gas Climate Change Initiative (GHG-CCI): comparison and quality assessment of near-surface-sensitive satellite-derived CO₂ and CH₄ global data sets. *Remote Sens. Environ.* 162:344–362, 2015.

Buchwitz et al., 2016: Buchwitz, M.; Reuter, M.; Aben, I.; Boesch, H.; Butz, A.; Detmers, R.G.; Frankenberg, C.; Hasekamp, O.P.; Parker, R.; Schneising, O.; Somkuti, P., ESA Greenhouse Gases Climate Change Initiative (GHG-CCI): Merged SCIAMACHY and GOSAT Level 3 gridded atmospheric column-average methane (XCH₄) product in Obs4MIPs format, Centre for Environmental Data Analysis, 10 October 2016, doi:10.5285/C965E4AC-D2AF-4BAA-9E99-A234E9BA0193, pp. 11, 2016.

Buchwitz et al., 2017: 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. 4 (CRDP#4), Version 5.0, 9. Feb. 2017, 2017.

Buchwitz et al., 2017a: Buchwitz, M.; Reuter, M.; Aben, I.; Boesch, H.; Butz, A.; Detmers, R.G.; Frankenberg, C.; Hasekamp, O.P.; Parker, R.; Schneising, O.; Somkuti, P., ESA Greenhouse Gases Climate Change Initiative (GHG-CCI): Merged SCIAMACHY and GOSAT Level 3 gridded atmospheric column-average methane (XCH₄) product in Obs4MIPs format version 2 (CRDP#4), Technical Note, pp. 11, 1 February 2017, 2017.

Buchwitz et al., 2017b: Buchwitz, M., Reuter, M., Schneising, O., Hewson, W., Detmers, R. G., Boesch, H., Hasekamp, O. P., Aben, I., Bovensmann, H., Burrows, J. P., Butz, A., Chevallier, F., Dils, B., Frankenberg, C., Heymann, J., Lichtenberg, G., De Mazière, M., Notholt, J., Parker, R., Warneke, T., Zehner, C., Griffith, D. W. T., Deutscher, N. M., Kuze, A., Suto, H., and Wunch, D.: Global satellite observations of column-averaged carbon dioxide and methane: The GHG-CCI XCO₂ and XCH₄ CRDP3 data set, *Remote Sensing of Environment* 203, 276–295, <http://dx.doi.org/10.1016/j.rse.2016.12.027>, 2017.

Burrows et al., 1995: 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.

Butz et al., 2011: Butz, A., Guerlet, S., Hasekamp, O., et al., Toward accurate CO₂ and CH₄ observations from GOSAT, *Geophys. Res. Lett.*, doi:10.1029/2011GL047888, 2011.



- Butz et al., 2012:** Butz, A., Galli, A., Hasekamp, O., Landgraf, J., Tol, P., and Aben, I.: Remote Sensing of Environment, TROPOMI aboard Sentinel-5 Precursor : Prospective performance of CH₄ retrievals for aerosol and cirrus loaded atmospheres, 120, 267-276, doi:10.1016/j.rse.2011.05.030, 2012.
- Chédin et al. 2003:** Chédin, A., Saunders, R., Hollingsworth, A., Scott, N. A., Matricardi, M., Etcheto, J., Clerbaux, C., Armante, R. and Crevoisier, C.: The feasibility of monitoring CO₂ from high resolution infrared sounders. *J. Geophys. Res.*, 108, ACH 6-1–6-19, doi: 10.1029/2001JD001443, 2003.
- Chevallier et al., 2005:** Chevallier, F., R. J. Engelen, and P. Peylin, The contribution of AIRS data to the estimation of CO₂ sources and sinks. *Geophys. Res. Lett.*, 32, L23801, doi:10.1029/2005GL024229, 2005.
- Chevallier et al., 2007:** Chevallier, F., F.-M. Bréon, and P. J. Rayner, Contribution of the Orbiting Carbon Observatory to the estimation of CO₂ sources and sinks: Theoretical study in a variational data assimilation framework. *J. Geophys. Res.*, 112, D09307, doi:10.1029/2006JD007375, 2007.
- Chevallier et al., 2009a:** Chevallier, F., R. J. Engelen, C. Carouge, T. J. Conway, P. Peylin, C. Pickett-Heaps, M. Ramonet, P. J. Rayner and I. Xueref-Remy, AIRS-based vs. surface-based estimation of carbon surface fluxes. *J. Geophys. Res.*, 114, D20303, doi:10.1029/2009JD012311, 2009.
- Chevallier et al., 2009b:** Chevallier, F., S. Maksyutov, P. Bousquet, F.-M. Bréon, R. Saito, Y. Yoshida, and T. Yokota, On the accuracy of the CO₂ surface fluxes to be estimated from the GOSAT observations. *Geophys. Res. Lett.*, 36, L19807, doi:10.1029/2009GL040108, 2009.
- Chevallier et al., 2010:** Chevallier, F., Feng, L., Boesch, H. Palmer, P., and Rayner, P., On the impact of transport model errors for the estimation of CO₂ surface fluxes from GOSAT observations, *Geophys. Res. Lett.*, 37, L21803, 2010.
- Chevallier et al., 2014:** Chevallier, F., Palmer, P.I., Feng, L., Boesch, H., O'Dell, C.W., Bousquet, P., Towards robust and consistent regional CO₂ flux estimates from in situ and space-borne measurements of atmospheric CO₂, *Geophys. Res. Lett.*, 41, 1065-1070, DOI: 10.1002/2013GL058772, 2014.
- Chevallier et al., 2016b:** Chevallier, F., et al., Climate Assessment Report (CAR), ESA Climate Change Initiative (CCI) GHG-CCI project, Version 3, 3 May 2016, 2016.
- Ciais et al., 2014:** 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, 2014.
- Ciais et al., 2015:** Ciais, P., et al.: Towards a European Operational Observing System to Monitor Fossil CO₂ emissions - Final Report from the expert group, <http://www.copernicus.eu/main/towards-european-operational-observing-system-monitor-fossil-co2-emissions>, pp. 68, October 2015, 2015.
- CMUG-RBD, 2010:** Climate Modelling User Group Requirements Baseline Document, Deliverable 1.2, Number D1.2, Version 1.3, 2 Nov 2010.
- Cogan et al., 2011:** 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.



Cressot et al., 2014: Cressot, C., F. Chevallier, P. Bousquet, et al., On the consistency between global and regional methane emissions inferred from SCIAMACHY, TANSO-FTS, IASI and surface measurements, *Atmos. Chem. Phys.*, 14, 577-592, 2014.

Crevoisier et al., 2004: Crevoisier, C., S. Heilliette, A. Chédin, S. Serrar, R. Armante, and N. A. Scott, Midtropospheric CO₂ concentration retrieval from AIRS observations in the tropics, *Geophys. Res. Lett.*, 31, L17106, doi:10.1029/2004GL020141, 2004.

Crevoisier et al., 2009: Crevoisier, C., Chédin, A., Matsueda, H., et al., First year of upper tropospheric integrated content of CO₂ from IASI hyperspectral infrared observations, *Atmos. Chem. Phys.*, 9, 4797-4810, 2009.

Crevoisier et al. 2009b: Crevoisier, C., Nobileau, D., Fiore, A., Armante, R., Chédin, A., and Scott, N. A.: Tropospheric methane in the tropics – first year from IASI hyperspectral infrared observations, *Atmos. Chem. Phys.*, 9, 6337–6350, doi:10.5194/acp-9-6337-2009, 2009b.

Crevoisier et al., 2013: Crevoisier, C., Nobileau, D., Armante, R., et al., The 2007–2011 evolution of tropical methane in the mid-troposphere as seen from space by MetOp-A/IASI, *Atmos. Chem. Phys.*, 13, 4279-4289, 2013.

Crisp et al., 2004: Crisp, D., Atlas, R. M., Breon, 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. S., 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, P., Pollock, R., Kenyon, D., and Schroll, S.: The Orbiting Carbon Observatory (OCO) mission, *Adv. Space Res.*, 34, 700-709, 2004.

Detmers et al., 2015: 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.

Dils et al., 2014: B. Dils, M. Buchwitz, M. Reuter, O. Schneising, H. Boesch, R. Parker, S. Guerlet, I. Aben, T. Blumenstock, J. P. Burrows, A. Butz, N. M. Deutscher, C. Frankenberg, F. Hase, O. P. Hasekamp, J. Heymann, M. De Mazière, J. Notholt, R. Sussmann, T. Warneke, D. Griffith, V. Sherlock, D. Wunch :The Greenhouse Gas Climate Change Initiative (GHG-CCI): Comparative validation of GHG-CCI SCIAMACHY/ENVISAT and TANSO-FTS/GOSAT CO₂ and CH₄ retrieval algorithm products with measurements from the TCCON network, *Atmos. Meas. Tech.*, 7, 1723-1744, 2014.

ESA-CCI-GHG-URDv2.1: Chevallier, F., et al., User Requirements Document (URD), ESA Climate Change Initiative (CCI) GHG-CCI project, Version 2.1, 19 Oct 2016, 2016.

Frankenberg et al., 2011: 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.

GCOS-154: Global Climate Observing System (GCOS): 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)”, December 2011, prepared by World Meteorological Organization (WMO), Intergovernmental Oceanographic Commission, United Nations Environment



Programme (UNEP), International Council for Science, Doc.: GCOS 154, link:

<http://cci.esa.int/sites/default/files/gcos-154.pdf>, 2011.

GCOS-200: The Global Observing System for Climate: Implementation Needs, World Meteorological Organization (WMO), GCOS-200 (GOOS-214), pp. 325, link:

http://unfccc.int/files/science/workstreams/systematic_observation/application/pdf/gcos_ip_10oct_2016.pdf, 2016.

Guerlet et al., 2013: Guerlet, S., S. Basu, A. Butz, M. Krol, P. Hahne, S. Houweling, O. P. Hasekamp and I. Aben, Reduced carbon uptake during the 2010 Northern Hemisphere summer from GOSAT, *Geophys. Res. Lett.*, doi: 10.1002/grl.50402, 2013.

Hachmeister et al., 2022: Hachmeister, J., Schneising, O., Buchwitz, M., Lorente, A., Borsdorff, T., Burrows, J. P., Notholt, J., and Buschmann, M.: On the influence of underlying elevation data on Sentinel-5 Precursor satellite methane retrievals over Greenland, *Atmos. Meas. Tech. Discuss.* [preprint; final version in Press], <https://doi.org/10.5194/amt-2022-102>, 2022.

Hayman et al., 2014: Hayman, G. D., O'Connor, F. M., Dalvi, M., Clark, D. B., Gedney, N., Huntingford, C., Prigent, C., Buchwitz, M., Schneising, O., Burrows, J. P., Wilson, C., Richards, N., Chipperfield, M., Comparison of the HadGEM2 climate-chemistry model against in-situ and SCIAMACHY atmospheric methane data, *Atmos. Chem. Phys.*, 14, 13257-13280, doi:10.5194/acp-14-13257-2014, 2014.

Hollmann et al., 2013: Hollmann, C.J. Merchant, R. Saunders, C. Downy, M. Buchwitz, A. Cazenave, E. Chuvieco, P. Defourny, G. de Leeuw, R. Forsberg, T. Holzer-Popp, F. Paul, S. Sandven, S. Sathyendranath, M. van Roozendaal, W. Wagner, 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, pp. 12, 2013.

Houweling et al., 2004: Houweling, S., Breon, F.-M., Aben, I., Rödenbeck, C., Gloor, M., Heimann, M. and Ciais, P.: Inverse modeling of CO₂ sources and sinks using satellite data: A synthetic inter-comparison of measurement techniques and their performance as a function of space and time, *Atmos. Chem. Phys.*, 4, 523-538, 2004.

Houweling et al., 2005: Houweling, S., Hartmann, W., Aben, I., Schrijver, H., Skidmore, J., Roelofs, G.-J., and Breon, F.-M.: Evidence of systematic errors in SCIAMACHY-observed CO₂ due to aerosols, *Atmos. Chem. Phys.*, 5, 3003–3013, 2005.

Houweling et al., 2015: Houweling, S., D. Baker, S. Basu, H. Boesch, A. Butz, F. Chevallier, F. Deng, E. J. Dlugokencky, L. Feng, A. Ganshin, O. Hasekamp, D. Jones, S. Maksyutov, J. Marshall, T. Oda, C.W. O'Dell, S. Oshchepkov, P. I. Palmer, P. Peylin, Z. Poussi, F. Reum, H. Takagi, Y. Yoshida, and R. Zhuravlev, An intercomparison of inverse models for estimating sources and sinks of CO₂ using GOSAT measurements, *J. Geophys. Res. Atmos.*, 120, 5253–5266, doi:10.1002/2014JD022962, 2015.

Hu et al., 2018: Hu, H., J. Landgraf, R. Detmers, T. Borsdorff, J. Aan de Brugh, I. Aben, A. Butz, O. Hasekamp, Toward Global Mapping of Methane With TROPOMI: First Results and Intersatellite Comparison to GOSAT, *Geophys. Res. Lett.*, Vol. 45, Issue 8, 3682-3689, <https://doi.org/10.1002/2018GL077259>, 2018.



- IPCC, 2013:** 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.
- JCGM, 2008:** JCGM/WG 1, Working Group 1 of the Joint Committee for Guides in Metrology, Evaluation of measurement data – Guide to the expression of uncertainty in measurement, http://www.bipm.org/utis/common/documents/jcgm/JCGM_100_2008_E.pdf, 2008.
- Kirschke et al., 2013:** 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.
- Kuze et al., 2009:** Kuze, A., Suto, H., Nakajima, M., and Hamazaki, T. (2009), 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.
- Kuze et al., 2014:** Kuze, A., Taylor, T., Kataoka, F., Bruegge, C., Crisp, D., Harada, M., Helmlinger, M., Inoue, M., Kawakami, S., Kikuchi, N., Mitomi, Y., Murooka, J., Naitoh, M., O'Brien, D., O'Dell, C., Ohyama, H., Pollock, H., Schwandner, F., Shiomi, K., Suto, H., Takeda, T., Tanaka, T., Urabe, T., Yokota, T., and Yoshida, Y. (2014), Long-term vicarious calibration of GOSAT short-wave sensors: techniques for error reduction and new estimates of radiometric degradation factors, *IEEE T. Geosci. Remote*, 52, 3991–4004, doi:10.1109/TGRS.2013.2278696, 2014.
- Kuze et al., 2016:** Kuze, A., Suto, H., Shiomi, K., Kawakami, S., Tanaka, M., Ueda, Y., Deguchi, A., Yoshida, J., Yamamoto, Y., Kataoka, F., Taylor, T. E., and Buijs, H. L.: Update on GOSAT TANSO-FTS performance, operations, and data products after more than 6 years in space, *Atmos. Meas. Tech.*, 9, 2445–2461, doi:10.5194/amt-9-2445-2016, 2016.
- Lauer et al., 2017:** Lauer, A., Eyring, V., Righi, M., Buchwitz, M., Defourny, P., Evaldsson, M., Friedlingstein, P., de Jeu, R., de Leeuw, G., Loew, A., Merchant, C. J., Mueller, B., Popp, T., Reuter, M., Sandven, S., Senfteleben, D., Stengel, M., Van Roozendaal, M., Wenzel, S., and Willen, U.: Benchmarking CMIP5 models with a subset of ESA CCI Phase 2 data using the ESMValTool, *Remote Sensing of Environment* 203, 9–39, <http://dx.doi.org/10.1016/j.rse.2017.01.007>, 2017.
- Machida et al. 2008:** Machida, T., Matsueda, H., Sawa, Y., Nakagawa, Y., Hirotani, K., Kondo, N., Goto, K., Nakazawa, T., Ishikawa, K., and Ogawa, T.: Worldwide measurements of atmospheric CO₂ and other trace gas species using commercial airlines, *J. Atmos. Ocean. Tech.*, 25(10), 1744–1754, doi:10.1175/2008JTECHA1082.1, 2008.
- Massart et al., 2016:** 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. Velasco, Ability of the 4-D-Var analysis of the GOSAT BESD XCO₂ retrievals to characterize atmospheric CO₂ at large and synoptic scales, *Atmos. Chem. Phys.*, 16, 1653–1671, doi:10.5194/acp-16-1653-2016, 2016.
- Matsueda et al. 2008:** Matsueda, H., Machida, T., Sawa, Y., Nakagawa, Y., Hirotani, K., Ikeda, H., Kondo, N., and Goto, K.: Evaluation of atmospheric CO₂ measurements from new flask air sampling of JAL airliner observation, *Pap. Meteorol. Geophys.*, 59, 1–17, 2008.
- McNorton et al., 2016:** McNorton, J., E. Gloor, C. Wilson, G. D. Hayman, N. Gedney, E. Comyn-Platt, T. Marthews, R. J. Parker, H. Boesch, and M. P. Chipperfield, Role of regional wetland emissions in atmospheric methane variability, *Geophys. Res. Lett.*, 43, doi:10.1002/2016GL070649, 2016.



- Meirink et al., 2006:** Meirink, J.-F., Eskes, H. J., and Goede, A. P. H., Sensitivity analysis of methane emissions derived from SCIAMACHY observations through inverse modelling, *Atmos. Chem. Phys.*, 6, 1275-1292, 2006.
- Membrive et al. 2016:** Membrive, O., Crevoisier, C., Sweeney, C., Danis, F., Hertzog, A., Engel, A., Bönisch, H., and Picon, L.: AirCore-HR: A high resolution column sampling to enhance the vertical description of CH₄ and CO₂, *Atmos. Meas. Tech. Discuss.*, doi:10.5194/amt-2016-236, 2016.
- Miller et al., 2007:** Miller, C. E., Crisp, D., DeCola, P. L., et al.: Precision requirements for space-based XCO₂ data, *J. Geophys. Res.*, 112, D10314, doi:10.1029/2006JD007659, 2007.
- National Research Council, 2004:** National Research Council, Climate Data Records from Environmental Satellites: Interim Report 2004, 150 pp., ISBN: 978-0-309-09168-8, DOI: <https://doi.org/10.17226/10944>, 2004.
- Nisbet et al., 2014:** Nisbet, E., Dlugokencky, E., and Bousquet, P.: Methane on the rise – again, *Science*, 343, 493–495, doi:10.1126/science.1247828, 2014.
- Noël et al., 2021:** Noël, S., Reuter, M., Buchwitz, M., Borchardt, J., Hilker, M., Bovensmann, H., Burrows, J. P., Di Noia, A., Suto, H., Yoshida, Y., Buschmann, M., Deutscher, N. M., Feist, D. G., Griffith, D. W. T., Hase, F., Kivi, R., Morino, I., Notholt, J., Ohyama, H., Petri, C., Podolske, J. R., Pollard, D. F., Sha, M. K., Shiomi, K., Sussmann, R., Te, Y., Velasco, V. A., and Warneke, T.: XCO₂ retrieval for GOSAT and GOSAT-2 based on the FOCAL algorithm, *Atmos. Meas. Tech.*, 14, 3837-3869, <https://doi.org/10.5194/amt-14-3837-2021>, 2021.
- Noël et al., 2022:** Noël, S., Reuter, M., Buchwitz, M., Borchardt, J., Hilker, M., Schneising, O., Bovensmann, H., Burrows, J. P., Di Noia, A., Parker, R. J., Suto, H., Yoshida, Y., Buschmann, M., Deutscher, N. M., Feist, D. G., Griffith, D. W. T., Hase, F., Kivi, R., Liu, C., Morino, I., Notholt, J., Oh, Y.-S., Ohyama, H., Petri, C., Pollard, D. F., Rettinger, M., Roehl, C. M., Rousogonous, C., Sha, M. K., Shiomi, K., Strong, K., Sussmann, R., Té, Y., Velasco, V. A., Vrekoussis, M., and Warneke, T.: Retrieval of greenhouse gases from GOSAT and GOSAT-2 using the FOCAL algorithm, *Atmos. Meas. Tech.*, 15, 3401–3437, <https://doi.org/10.5194/amt-15-3401-2022>, 2022.
- Pandey et al., 2016:** Pandey, S., S. Houweling, M. Krol, I. Aben, F. Chevallier, E. J. Dlugokencky, L. V. Gatti, E. Gloor, J. B. Miller, R. Detmers, T. Machida, T. Roeckmann, Inverse modeling of GOSAT-retrieved ratios of total column CH₄ and CO₂ for 2009 and 2010, *Atmos. Chem. Phys.*, 16, 5043–5062, doi:10.5194/acp-16-5043-2016, 2016.
- Parker et al., 2011:** 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.
- Parker et al., 2016:** Parker, R. J., H. Boesch, M. J. Wooster, D. P. Moore, A. J. Webb, D. Gaveau, and D. Murdiyarso, Atmospheric CH₄ and CO₂ enhancements and biomass burning emission ratios derived from satellite observations of the 2015 Indonesian fire plumes, *Atmos. Chem. Phys.*, *Atmos. Chem. Phys.*, 16, 10111-10131, doi:10.5194/acp-16-10111-2016, 2016.
- Parkinson et al., 2006:** Parkinson, C., A. Ward and M. King, Earth Science Reference Handbook, NASA, Washington DC, 2006.



Pillai et al., 2016: Pillai, D., Buchwitz, M., Gerbig, C., Koch, T., Reuter, M., Bovensmann, H., Marshall, J., and Burrows, J. P.: Tracking city CO₂ emissions from space using a high resolution inverse modeling approach: A case study for Berlin, Germany, *Atmos. Chem. Phys.*, 16, 9591-9610, doi:10.5194/acp-16-9591-2016, 2016.

PQAR GHG, 2023: Buchwitz, M., Barr, A., Boesch, H., Borsdorff, T., Crevoisier, C., Di Noia, A., Hasekamp, O. P., Landgraf, J., Meilhac, N., Parker, R., Reuter, M., Schneising-Weigel, O.: Product Quality Assessment Report (PQAR) – Main document for Greenhouse Gas (GHG: CO₂ & CH₄) data set CDR6 (01.2003-12.2021), C3S project C3S2_312a_Lot2_DLR, v6.3, 2023. Link: https://www.iup.uni-bremen.de/carbon_ghg/docs/C3S/CDR6_2003-2021/C3S2_312a_Lot2_D-WP2_PQAR-2022-GHG_MAIN_v6.3.pdf

PUGS GHG, 2023: Buchwitz, M., Barr, A., Boesch, H., Borsdorff, T., Crevoisier, C., Di Noia, A., Hasekamp, O. P., Landgraf, J., Meilhac, N., Parker, R., Reuter, M., Schneising-Weigel, O.: Product User Guide and Specification (PUGS) – Main document for Greenhouse Gas (GHG: CO₂ & CH₄) data set CDR6 (01.2003-12.2021), C3S project C3S2_312a_Lot2_DLR, v6.3, 2023. Link: https://www.iup.uni-bremen.de/carbon_ghg/docs/C3S/CDR6_2003-2021/C3S2_312a_Lot2_D-WP2_PUGS-2022-GHG_MAIN_v6.3.pdf

Rayner and O'Brien, 2001: Rayner, P. J., and O'Brien, D.M.: The utility of remotely sensed CO₂ concentration data in surface inversions, *Geophys. Res. Lett.*, 28, 175-178, 2001.

Reuter et al. 2011: Reuter, M., Bovensmann, H., Buchwitz, M., Burrows, J. P., Connor, B. J., Deutscher, N. M., Griffith, D.W. T., Heymann, J., Keppel-Aleks, G., Messerschmidt, J., and et al.: Retrieval of atmospheric CO₂ with enhanced accuracy and precision from SCIAMACHY: Validation with FTS measurements and comparison with model results., *Journal of Geophysical Research*, 116, doi:10.1029/2010JD015047, URL <http://dx.doi.org/10.1029/2010JD015047>, 2011.

Reuter et al., 2013: Reuter, M. H. Bösch, H. Bovensmann, A. Bril, M. Buchwitz, A. Butz, J. P. Burrows, C. W. O'Dell, S. Guerlet, O. Hasekamp, J. Heymann, N. Kikuchi, S. Oshchepkov, R. Parker, S. Pfeifer, O. Schneising, T. Yokota, and Y. Yoshida, A joint effort to deliver satellite retrieved atmospheric CO₂ concentrations for surface flux inversions: The ensemble median algorithm EMMA, *Atmos. Chem. Phys.*, 13, 1771-1780, 2013.

Reuter et al., 2014a: Reuter, M., M. Buchwitz, A. Hilboll, A. Richter, O. Schneising, M. Hilker, J. Heymann, H. Bovensmann and J. P. Burrows, Decreasing emissions of NO_x relative to CO₂ in East Asia inferred from satellite observations, *Nature Geoscience*, 28 Sept. 2014, doi:10.1038/ngeo2257, pp.4, 2014.

Reuter et al., 2014b: Reuter, M., M. Buchwitz, M. Hilker, J. Heymann, O. Schneising, D. Pillai, H. Bovensmann, J. P. Burrows, H. Bösch, R. Parker, A. Butz, O. Hasekamp, C. W. O'Dell, Y. Yoshida, C. Gerbig, T. Nehrkorn, N. M. Deutscher, T. Warneke, J. Notholt, F. Hase, R. Kivi, R. Sussmann, T. Machida, H. Matsueda, and Y. Sawa, Satellite-inferred European carbon sink larger than expected, *Atmos. Chem. Phys.*, 14, 13739-13753, doi:10.5194/acp-14-13739-2014, 2014.

Reuter et al., 2016: Reuter, M.; Buchwitz, M.; Aben, I.; Boesch, H.; Butz, A.; Detmers, R.G.; Hasekamp, O.P.; Heymann, J.; Parker, R.; Schneising, O.; Somkuti, P., ESA Greenhouse Gases Climate Change Initiative (GHG_cci): Merged SCIAMACHY and GOSAT Level 3 gridded atmospheric column-average carbon dioxide (XCO₂) product in Obs4MIPs format. Centre for Environmental Data Analysis, 10 October 2016, doi:10.5285/3FAE8371-0CBB-4B21-9EA6-7A1FC293C4A2, pp. 11, 2016.



- Reuter et al., 2017:** Reuter, M., M. Buchwitz, M. Hilker, J. Heymann, H. Bovensmann, J. Burrows, S. Houweling, Y. Liu, R. Nassar, F. Chevallier, P. Ciais, J. Marshall, and M. Reichstein, 2016: How much CO₂ is taken up by the European terrestrial biosphere ?, *Bull. Amer. Meteor. Soc.* doi:10.1175/BAMS-D-15-00310.1, 24 April 2017, 665-671, 2017.
- Reuter et al., 2017a:** Reuter, M.; Buchwitz, M.; Aben, I.; Boesch, H.; Butz, A.; Detmers, R.G.; Hasekamp, O.P.; Heymann, J.; Parker, R.; Schneising, O.; Somkuti, P., ESA Greenhouse Gases Climate Change Initiative (GHG-CCI): Merged SCIAMACHY and GOSAT Level 3 gridded atmospheric column-average carbon dioxide (XCO₂) product in Obs4MIPs format version 2 (CRDP#4), Technical Note, pp. 11, 1 February 2017, 2017.
- Reuter et al., 2020:** Reuter, M., Buchwitz, M., Schneising, O., Noel, S., Bovensmann, H., Burrows, J. P., Boesch, H., Di Noia, A., Anand, J., Parker, R. J., Somkuti, P., Wu, L., Hasekamp, O. P., Aben, I., Kuze, A., Suto, H., Shiomi, K., Yoshida, Y., Morino, I., Crisp, D., O'Dell, C. W., Notholt, J., Petri, C., Warneke, T., Velasco, V. A., Deutscher, N. M., Griffith, D. W. T., Kivi, R., Pollard, D. F., Hase, F., Sussmann, R., Te, Y. V., Strong, K., Roche, S., Sha, M. K., De Maziere, M., Feist, D. G., Iraci, L. T., Roehl, C. M., Retscher, C., and Schepers, D.: Ensemble-based satellite-derived carbon dioxide and methane column-averaged dry-air mole fraction data sets (2003-2018) for carbon and climate applications, *Atmos. Meas. Tech.*, 13, 789-819, <https://doi.org/10.5194/amt-13-789-2020>, 2020.
- Rodgers, 2000:** Rodgers C. D.: *Inverse Methods for Atmospheric Sounding: Theory and Practice*, World Scientific Publishing, 2000.
- Ross et al., 2013:** Ross, A. N., Wooster, M. J., Boesch, H., Parker, R., First satellite measurements of carbon dioxide and methane emission ratios in wildfire plumes, *Geophys. Res. Lett.*, 40, 1-5, doi:10.1002/grl.50733, 2013.
- Schaefer et al., 2016:** Schaefer, H., Mikaloff Fletcher, S. E., Veidt, C., Lassey, K. R., Brailsford, G. W., Bromley, T. M., Dlugokencky, E. J., Michel, S. E., Miller, J. B., Levin, I., Lowe, D. C., Martin, R. J., Vaughn, B. H., and White, J. W. C.: A 21st-century shift from fossil-fuel to biogenic methane emissions indicated by ¹³CH₄, *Science*, Vol. 352, Issue 6281, pp. 80-84, doi 10.1126/science.aad2705, 2016.
- Shindell et al., 2013:** Shindell, D. T., Pechony, O., Voulgarakis, A., et al. (2013), Interactive ozone and methane chemistry in GISS-E2 historical and future climate simulations, *Atmos. Chem. Phys.*, 13, 2653–2689, doi:10.5194/acp-13-2653-2013, 2013.
- Schepers et al., 2012:** Schepers, D., Guerlet, S., Butz, A., Landgraf, J., Frankenberg, C., Hasekamp, O., Blavier, J.-F., Deutscher, N. M., Griffith, D. W. T., Hase, F., Kyro, E., Morino, I., Sherlock, V., Sussmann, R., Aben, I. (2012), 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.
- Schneising et al., 2011:** 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.
- Schneising et al., 2014a:** 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, 2014.

Schneising et al., 2014b: 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, 2014.

Schneising et al., 2019: Schneising, O., Buchwitz, M., Reuter, M., Bovensmann, H., Burrows, J. P., Borsdorff, T., Deutscher, N. M., Feist, D. G., Griffith, D. W. T., Hase, F., Hermans, C., Iraci, L. T., Kivi, R., Landgraf, J., Morino, I., Notholt, J., Petri, C., Pollard, D. F., Roche, S., Shiomi, K., Strong, K., Sussmann, R., Velazco, V. A., Warneke, T., and Wunch, D.: A scientific algorithm to simultaneously retrieve carbon monoxide and methane from TROPOMI onboard Sentinel-5 Precursor, *Atmos. Meas. Tech.*, 12, 6771-6802, <https://doi.org/10.5194/amt-12-6771-2019>, <https://doi.org/10.5194/amt-12-6771-2019>, 2019.

Schneising et al., 2020: Schneising, O., Buchwitz, M., Reuter, M., Vanselow, S., Bovensmann, H., and Burrows, J. P.: Remote sensing of methane leakage from natural gas and petroleum systems revisited, *Atmos. Chem. Phys.*, 20, 9169-9182, <https://doi.org/10.5194/acp-20-9169-2020>, 2020.

Suto et al., 2021: Suto, H., Kataoka, F., Kikuchi, N., Knuteson, R. O., Butz, A., Haun, M., Buijs, H., Shiomi, K., Imai, H., and Kuze, A.: Thermal and near-infrared sensor for carbon observation Fourier transform spectrometer-2 (TANSO-FTS-2) on the Greenhouse gases Observing SATellite-2 (GOSAT-2) during its first year in orbit, *Atmos. Meas. Tech.*, 14, 2013-2039, <https://doi.org/10.5194/amt-14-2013-2021>, 2021.

TRD GHG, 2017: Buchwitz, M., Aben, I., Anand, J., Armante, R., Boesch, H., Crevoisier, C., Detmers, R. G., Hasekamp, O. P., Reuter, M., Schneising-Weigel, O., Target Requirement Document, Copernicus Climate Change Service (C3S) project on satellite-derived Essential Climate Variable (ECV) Greenhouse Gases (CO₂ and CH₄) data products (project C3S_312a_Lot6), Version 1.3, 20-October-2017, pp. 53, 2017.

TRD GAD GHG, 2020: Buchwitz, M., Aben, I., Armante, R., Boesch, H., Crevoisier, C., Hasekamp, O. P., Wu, L., Reuter, M., Schneising-Weigel, O., Target Requirement and Gap Analysis Document, Copernicus Climate Change Service (C3S) project on satellite-derived Essential Climate Variable (ECV) Greenhouse Gases (CO₂ and CH₄) data products (project C3S_312b_Lot2), Version 2.11, 9-April-2020, pp. 80, 2020.

TRD GAD GHG, 2021: Buchwitz, M., Reuter, M., Schneising-Weigel, O., Aben, I., Wu, L., Hasekamp, O. P., Boesch, H., Di Noia, A., Crevoisier, C., Armante, R.: Target Requirement and Gap Analysis Document, Copernicus Climate Change Service (C3S) project on satellite-derived Essential Climate Variable (ECV) Greenhouse Gases (CO₂ and CH₄) data products, Version 3.1, 19-February-2021, pp. 81, 2021.

Turner et al., 2015: Turner, A. J., D. J. Jacob, K. J. Wecht, J. D. Maasakkers, S. C. Biraud, H. Boesch, K. W. Bowman, N. M. Deutscher, M. K. Dubey, D. W. T. Griffith, F. Hase, A. Kuze, J. Notholt, H. Ohyama, R. Parker, V. H. Payne, R. Sussmann, V. A. Velazco, T. Warneke, P. O. Wennberg, and D. Wunch, Estimating global and North American methane emissions with high spatial resolution using GOSAT satellite data, *Atmos. Chem. Phys.*, 15, 7049-7069, doi:10.5194/acp-15-7049-2015, 2015.



- Turner et al., 2016:** Turner, A. J., D. J. Jacob, J. Benmergui, S. C. Wofsy, J. D. Maasakkers, A. Butz, O. Hasekamp, and S. C. Biraud, A large increase in U.S. methane emissions over the past decade inferred from satellite data and surface observations, *Geophys. Res. Lett.*, 43, 2218–2224, doi:10.1002/2016GL067987, 2016.
- Veefkind et al. 2012:** 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.
- Velazco et al. 2011:** Velazco, V. A., Buchwitz, M., Bovensmann, H., Reuter, M., Schneising, O., Heymann, J., Krings, T., Gerilowski, K., and Burrows, J. P.: Towards space based verification of CO₂ emissions from strong localized sources: fossil fuel power plant emissions as seen by a CarbonSat constellation, *Atmos. Meas. Tech.*, 4, 2809–2822, 2011.
- Werschek, 2015:** Werschek, M., EUMETSAT Satellite Application Facility on Climate Monitoring, C3S Climate Data Store workshop, Reading, UK, 3–6 March 2015.
<http://www.ecmwf.int/sites/default/files/elibrary/2015/13546-existing-solutions-eumetsat-satellite-application-facility-climate-monitoring.pdf>
- Wofsy et al. 2012:** Wofsy, S. C., Daube, B. C., Jimenez, R., et al.: HIPPO Merged 10-second Meteorology, Atmospheric Chemistry, Aerosol Data (R 20121129), Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA, release 29 November 2012, 2012.
- Wunch et al. 2010:** Wunch, D., Toon, G. C., Wennberg, P. O., Wofsy, S. C., Stephens, B. B., Fischer, M. L., Uchino, O., Abshire, J. B., Bernath, P., Biraud, S. C., Blavier, J.-F. L., Boone, C., Bowman, K. P., Browell, E. V., Campos, T., Connor, B. J., Daube, B. C., Deutscher, N. M., Diao, M., Elkins, J. W., Gerbig, C., Gottlieb, E., Griffith, D. W. T., Hurst, D. F., Jiménez, R., Keppel-Aleks, G., Kort, E. A., Macatangay, R., Machida, T., Matsueda, H., Moore, F., Morino, I., Park, S., Robinson, J., Roehl, C. M., Sawa, Y., Sherlock, V., Sweeney, C., Tanaka, T., and Zondlo, M. A.: Calibration of the Total Carbon Column Observing Network using aircraft profile data, *Atmospheric Measurement Techniques*, 3, 1351–1362, doi:10.5194/amt-3-1351-2010, URL <http://www.atmos-meas-tech.net/3/1351/2010/>, 2010.
- Wunch et al. 2011:** Wunch, D., Toon, G. C., Blavier, J.-F. L., Washenfelder, R. A., Notholt, J., Connor, B. J., Griffith, D. W. T., Sherlock, V., and Wennberg, P. O.: The Total Carbon Column Observing Network (TCCON), *Philosophical Transactions of the Royal Society of London, Series A: Mathematical, Physical and Engineering Sciences*, 369, 2087–2112, doi:10.1098/rsta.2010.0240, 2011.
- Wunch et al. 2015:** Wunch, D., Toon, G. C., Sherlock, V., Deutscher, N. M., Liu, X., Feist, D. G., 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.
- Yoshida et al. 2013:** Yoshida, Y., Kikuchi, N., Morino, I., Uchino, O., Oshchepkov, S., Bril, A., Saeki, T., Schutgens, N., Toon, G. C., Wunch, D., Roehl, C. M., Wennberg, P. O., Griffith, D. W. T., Deutscher, N.



M., Warneke, T., Notholt, J., Robinson, J., Sherlock, V., Connor, B., Rettinger, M., Sussmann, R., Ahonen, P., Heikkinen, P., Kyrö, E., Mendonca, J., Strong, K., Hase, F., Dohe, S., and Yokota, T.: Improvement of the retrieval algorithm for GOSAT SWIR XCO₂ and XCH₄ and their validation using TCCON data, *Atmos. Meas. Tech.*, 6, 1533–1547, doi:10.5194/amt-6-1533-2013, 2013.

Copernicus Climate Change Service

ECMWF - Shinfield Park, Reading RG2 9AX, UK

Contact: <https://support.ecmwf.int/>

climate.copernicus.eu

copernicus.eu

ecmwf.int