



Product User Guide and Specification (PUGS) – ANNEX E for IASI CO₂ and CH₄ (v9.1) and AIRS CO₂ mid-tropospheric products

C3S_312b_Lot2_DLR – Atmosphere

Issued by: C. Crevoisier, LMD/CNRS, France

Date: 18/02/2021

Ref: C3S_D312b_Lot2.3.2.3-v3.0_PUGS-GHG_ANNEX-E_v5.0

Official reference number service contract: 2018/C3S_312b_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 of the European Union (Delegation Agreement signed on 11/11/2014). All information in this document is provided "as is" and no guarantee or warranty is given that the information is fit for any particular purpose. The user thereof uses the information at its sole risk and liability. For the avoidance of all doubts, the European Commission and the European Centre for Medium-Range Weather Forecasts has no liability in respect of this document, which is merely representing the authors view.



Contributors

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

M. Buchwitz

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

C. Crevoisier

R. Armante



Table of Contents

History of modifications	5
Related documents	6
Acronyms	7
General definitions	10
Scope of document	11
Executive summary	12
1. Product description	13
1.1 The IASI instrument onboard the Metop platforms	13
1.2 CH ₄ and CO ₂ mid-tropospheric column averaged mole fractions	13
1.3 AIRS CO ₂ mid-tropospheric column averaged mole fractions	19
2. Target requirements	20
3. Data usage information	21
3.1 Product content and format	21
3.2 Tools for reading data	22
3.3 Recommended data usage	23
3.4 Known limitations and issues	23
References	24



History of modifications

Version	Date	Description of modification	Chapters / Sections
1.3	20-October-2017	New document for data set CDR1 (until 2016)	All
2.0	4-October-2018	Update for CDR2 (until 2017)	All
3.0	12-August-2019	Update for CDR3 (until 2018) with additional information on Metop-C	All, esp. Sects. 1.1 and 1.2
3.1	03-November-2019	Update after review by Assimila: Correction of typos and broken links. Improved typesetting of equations.	All
4.0	18-August-2020	Update for CRD4 (until 2019) with new version of the retrieval code	All
5.0	18-February-2021	Update for CRD5 (until 2020)	All



Related documents

Reference ID	Document
D1	Main PUGS: Buchwitz, M., et al., Product User Guide and Specification (PUGS) – Main document for Greenhouse Gas (GHG: CO ₂ & CH ₄) data set CDR 5 (01.2003-06.2020), project C3S_312b_Lot2_DLR – Atmosphere, v5.0, 2021. <i>(this document is an ANNEX to the Main PUGS)</i>
D2	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 (CO ₂ and CH ₄) data products (project C3S_312b_Lot2), Version 2.11, 9-April-2020, pp. 80, 2020.
D3	Related PQAR: Crevoisier, C., et al.: Product Quality Assessment Report (PQAR) – ANNEX E for IASI CO ₂ and CH ₄ and AIRS CO ₂ mid-tropospheric products, C3S project C3S_312b_Lot2_DLR, v5.0, 2021.



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
GOME	Global Ozone Monitoring Experiment
GMES	Global Monitoring for Environment and Security
GOSAT	Greenhouse Gases Observing Satellite
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 <i>neuronal</i> network mid/upper tropospheric CO ₂ and CH ₄ retrieval algorithm
NOAA	National Oceanic and Atmospheric Administration
Obs4MIPs	Observations for Climate Model Intercomparisons
OCO	Orbiting Carbon Observatory
OE	Optimal Estimation
PBL	Planetary Boundary Layer
ppb	Parts per billion
ppm	Parts per million
PR	(light path) PROxy retrieval method
PVIR	Product Validation and Intercomparison Report
QA	Quality Assurance
QC	Quality Control
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
SWIR	Short Wave Infra Red
TANSO	Thermal And Near infrared Sensor for carbon Observation
TANSO-FTS	Fourier Transform Spectrometer on GOSAT
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

Table 1 lists some general definitions relevant for this document.

Table 1: General definitions.

Item	Definition
XCO ₂	Column-averaged dry-air mixing ratios (mole fractions) of CO ₂
XCH ₄	Column-averaged dry-air mixing ratios (mole fractions) of CH ₄
L1	Level 1 satellite data product: geolocated radiance (spectra)
L2	Level 2 satellite-derived data product: Here: CO ₂ and CH ₄ information for each ground-pixel
L3	Level 3 satellite-derived data product: Here: Gridded CO ₂ and CH ₄ information, e.g., 5 deg times 5 deg, monthly
L4	Level 4 satellite-derived data product: Here: Surface fluxes (emission and/or uptake) of CO ₂ and CH ₄



Scope of document

This document is a Product User Guide and Specification (PUGS) for the Copernicus Climate Change Service (C3S, <https://climate.copernicus.eu/>) greenhouse gas (GHG) component as covered by project C3S_312b_Lot2.

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

The satellite-derived GHG data products are:

- Column-average 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).

This document describes the C3S products CO₂_IASA_NLIS (v9.1), CH₄_IASA_NLIS (v9.1), CO₂_IASB_NLIS (v9.1), CH₄_IASB_NLIS (v9.1), CO₂_AIRS_NLIS (v3.0).

These products are mid-tropospheric CO₂ and CH₄ Level 2 products as retrieved from the IASI sensors on Metop-A and Metop-B and mid-tropospheric CO₂ from AIRS sensor on Aqua using algorithms developed at CNRS-LMD, France.



Executive summary

This document describes the data and metadata delivered to the Copernicus Climate Change Service (C3S) for the Level 2 CO₂ and CH₄ data products retrieved from IASI and AIRS observations at CNRS-LMD. These products are mid-tropospheric-averaged dry-air mixing ratios (mole fractions) of CH₄ and CO₂, retrieved at 9:30 am/pm (local time) from observations made by the IASI and AMSU instruments onboard the European Metop-A (since July 2006) and Metop-B (since February 2013) platforms. They also include CO₂ mid-tropospheric-averaged dry-air mixing ratios derived from observations made by AIRS and AMSU instruments flying onboard Aqua for the period 2003-2005.

Data are provided as daily netCDF files available at the C3S website. Their content (data format, averaging kernels, geolocation information, etc.) as well as information on performances and limitations will be given.



1. Product description

1.1 The IASI instrument onboard the Metop platforms

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 (<https://iasi.cnes.fr/en/IASI/index.htm>). 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 onboard the polar orbiting Meteorological Operational Platform (Metop-A), in September 2012 onboard Metop-B and in October 2018 onboard Metop-C. The 3 instruments have been declared operational in July 2007, February 2013 and July 2019, respectively.

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 apodization. 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 at 9:30 am/pm local time.

The combined use of both Metop satellites, which are flying on the same orbit but with nearly half an orbit out of phase, yields a complete coverage of the Earth in one day. With the recent launch of Metop-C, in 2018, these time series will cover about 20 years. In order to be useful for climate studies, it is mandatory that the time series derived from the 3 successive platforms are consistent in order to allow studying trends and growth rates.

1.2 CH₄ and CO₂ mid-tropospheric column averaged mole fractions

Four Level 2 products are described in this document:

- CH₄_IASA_NLIS: mid-tropospheric column averaged mole fractions of CH₄ retrieved from IASI onboard Metop-A.
- CH₄_IASB_NLIS: mid-tropospheric column averaged mole fractions of CH₄ retrieved from IASI onboard Metop-B.
- CO₂_IASA_NLIS: mid-tropospheric column averaged mole fractions of CO₂ retrieved from IASI onboard Metop-A.
- CO₂_IASB_NLIS: mid-tropospheric column averaged mole fractions of CO₂ retrieved from IASI onboard Metop-B.

Each of these products have been are retrieved from simultaneous observations of the IASI and AMSU instruments flying together onboard the Metop satellites using a non-linear inference scheme using Multi-Layer Perceptrons with 2 hidden layers. IASI hyperspectral observations in the



thermal infrared at 7.7 μm (resp. 15 μm), which are sensitive to both temperature and gas concentrations of CH_4 (resp. CO_2) are used in conjunction with microwave observations from the AMSU instruments, only sensitive to temperature, to decorrelate both signals (*Crevoisier et al., 2009a, 2009b, 2013*).

Potential radiative systematic biases existing between simulations used in the inference scheme and observations are computed for each channel by averaging, over the instruments full years of operation, the differences between simulations and collocated (in time and space) satellite observations. The simulations are performed using the 4A/OP-2009 forward model (Scott and Chédin, 1981; <https://4aop.noveltis.com/>), which is based on the updated 2011 version of the GEISA spectroscopic database (available at <https://geisa.aeris-data.fr>) (Jacquinet-Husson et al., 2011), and radiosonde measurements from the Analyzed RadioSoundings Archive database (available at <http://ara.lmd.polytechnique.fr>). IASI calibrated radiance spectra (level1c) are received through the EUMETCast near real time data distribution service via the French Ether center (<https://www.aeris-data.fr/>).

The retrieved CO_2 and CH_4 integrated columns are weighted to the tropical mid-troposphere with peak sensitivity at about 230 hPa (~ 11 km), half the peak sensitivity at 100 and 500 hPa (~ 6 and 16 km), and no sensitivity to the surface. Retrievals are performed over land and sea, by night and day (9:30 am/pm local time) for clear-sky only (no clouds, no aerosols). The CO_2 retrievals are limited to the tropical region (30N:30S) because of the greater stability of the temperature atmospheric profile, which helps decorrelating temperature from gas in the observed radiances, yielding a much better precision compared to the extratropics.

Through comparisons with regular aircraft (*Machida et al., 2008*) or balloon (*Membrive et al., 2017*) measurements as well as observations made at the surface, it has been shown that, once the radiometric characterization of the instruments is performed, IASI and AMSU capture well the trend and interannual variation of CH_4 , with an excellent agreement with the rate of increase measured at the surface, giving confidence in the ability of IASI to follow its evolution over the 20 years of the Metop program.

Figure 1 shows the daily coverage provided by the use of both Metop-A and Metop-B in terms of mid-tropospheric CH_4 . Figures 2 shows the monthly time series of mid-tropospheric CO_2 as retrieved from IASI onboard Metop-A.

Figure 1: Daily maps of CH₄ mid-tropospheric column averaged mole fraction retrieved from Metop-A, from Metop-B and from both platforms for September, 15th, 2013.

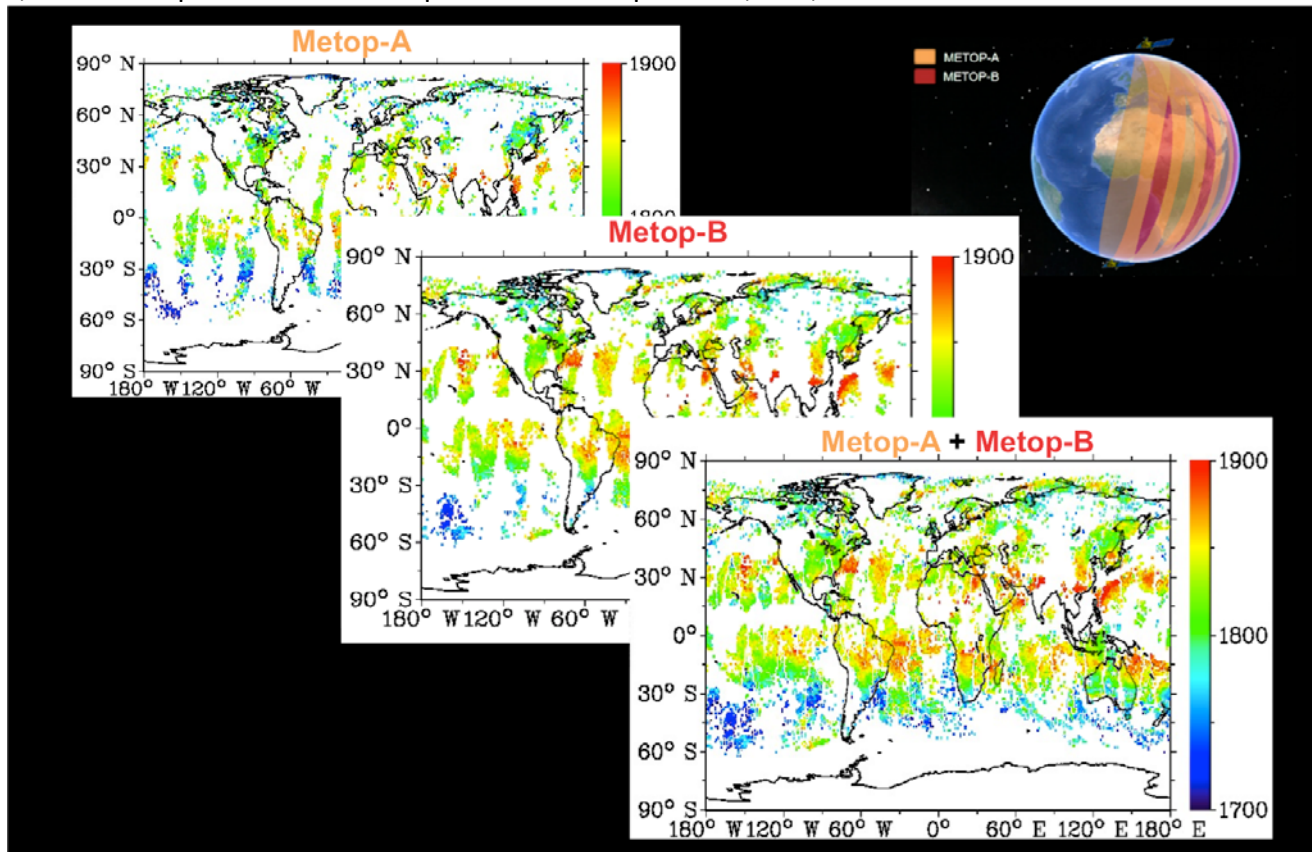




Figure 2: Seasonal maps of mid-tropospheric CH₄ (v9.1) retrieved from Metop-A only (JAS 2007-OND 2012), from Metop-A and Metop-B (JFM 2013-OND 2020).

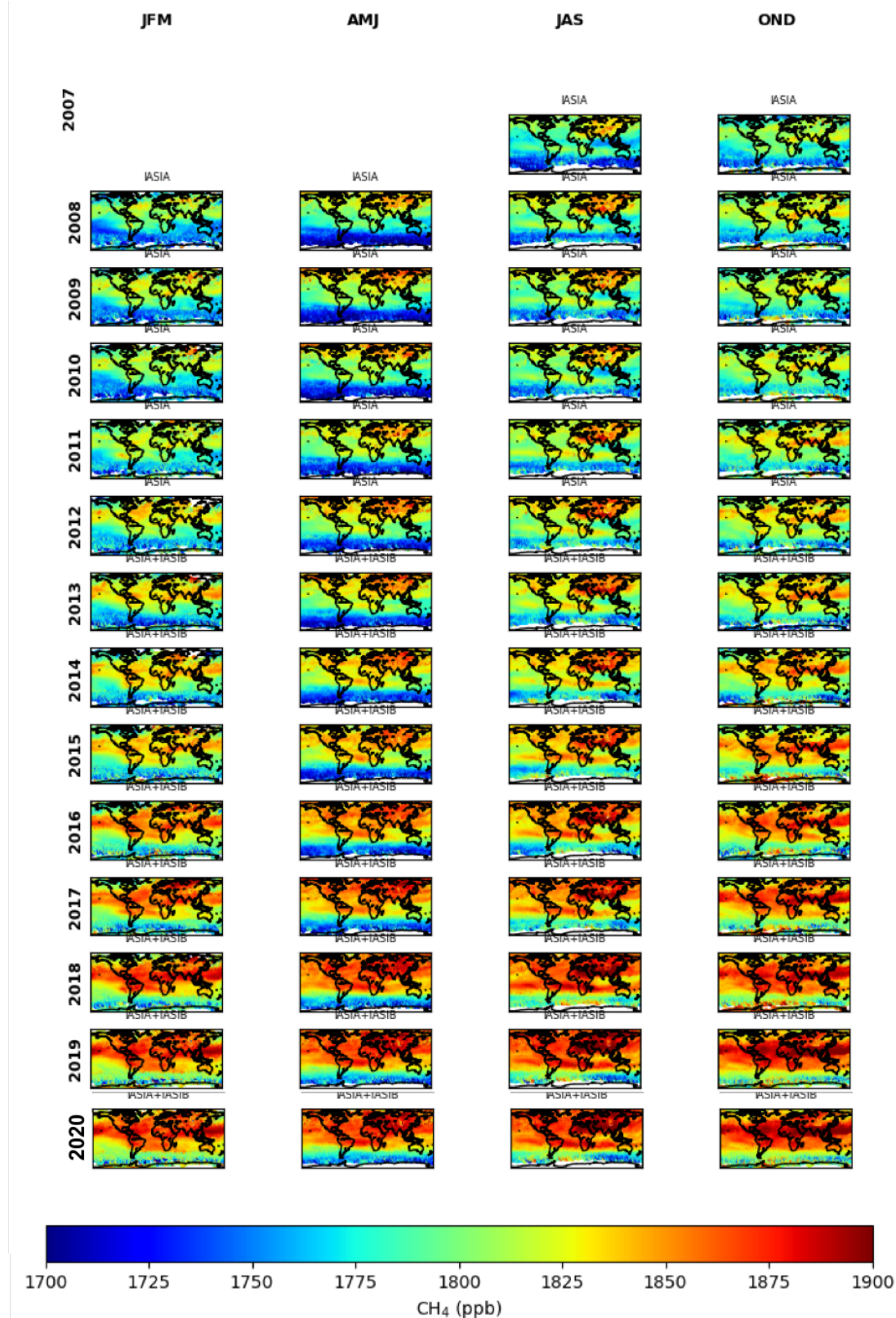




Figure 3: Same as Fig. 2 but mid-tropospheric CO₂ (v9.1).

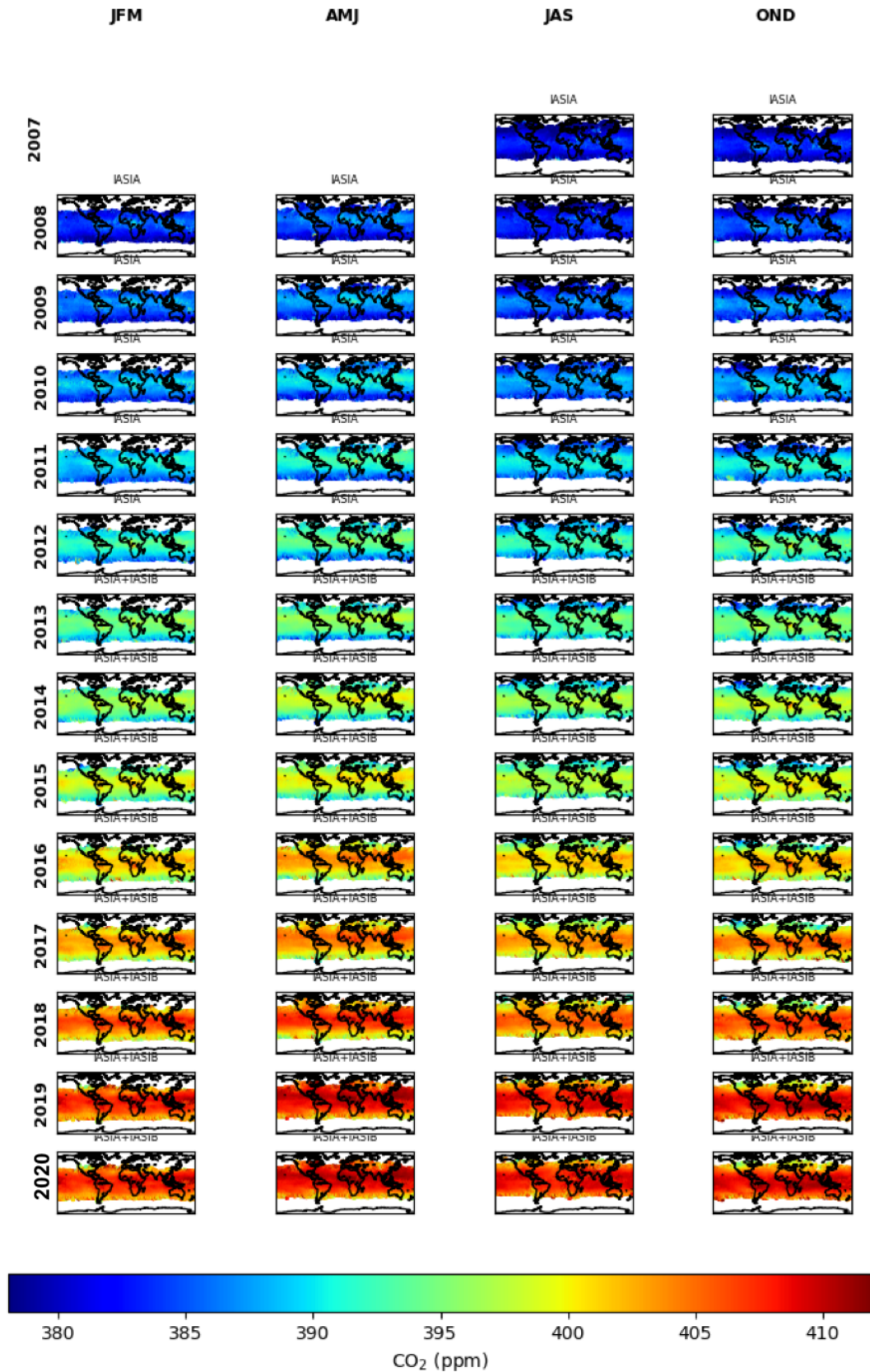


Figure 4. Monthly evolution displayed as a function of latitude of CO₂ mid-tropospheric column averaged mole fraction retrieved from Metop-A and Metop-B combined (version 9.1).

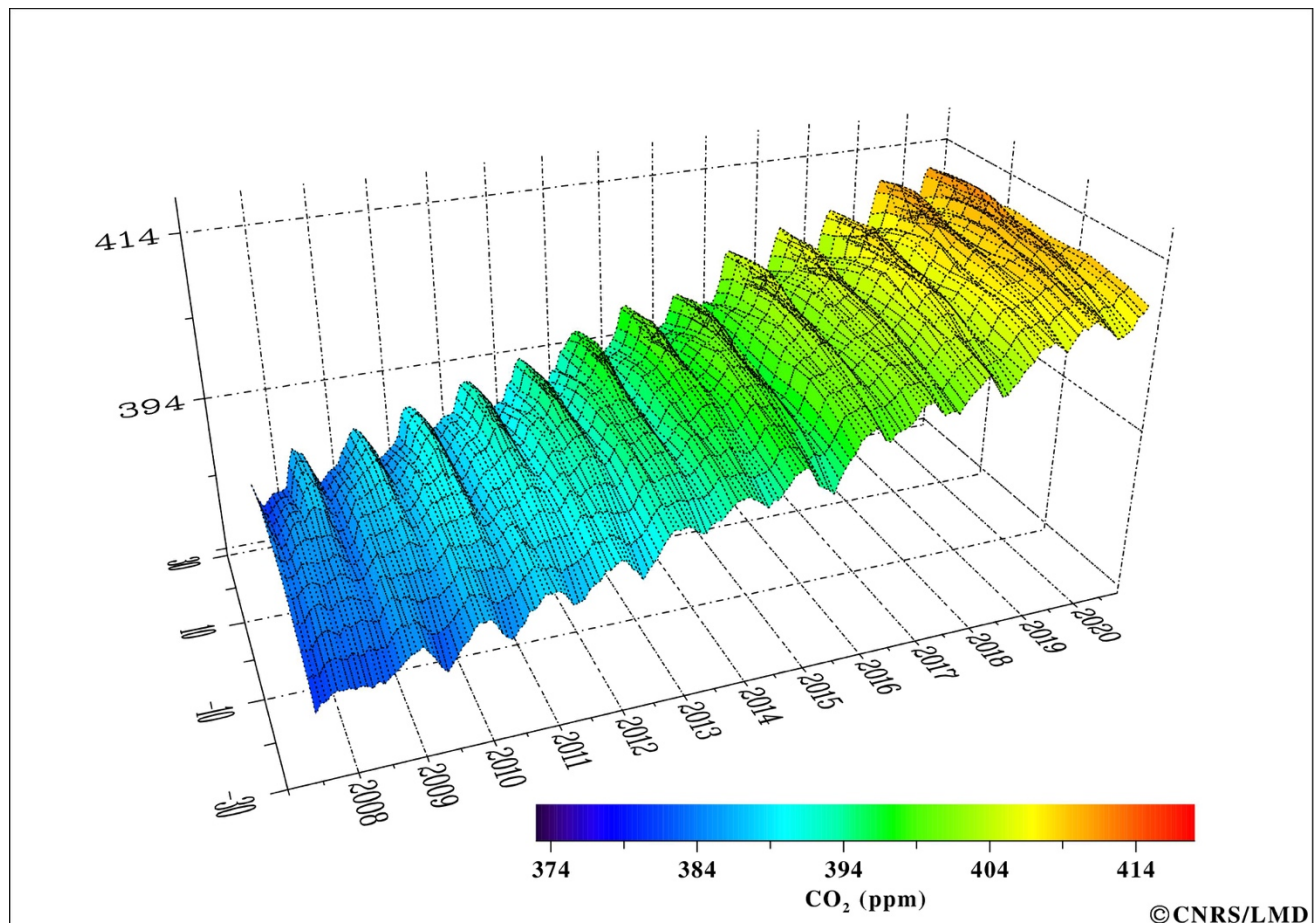
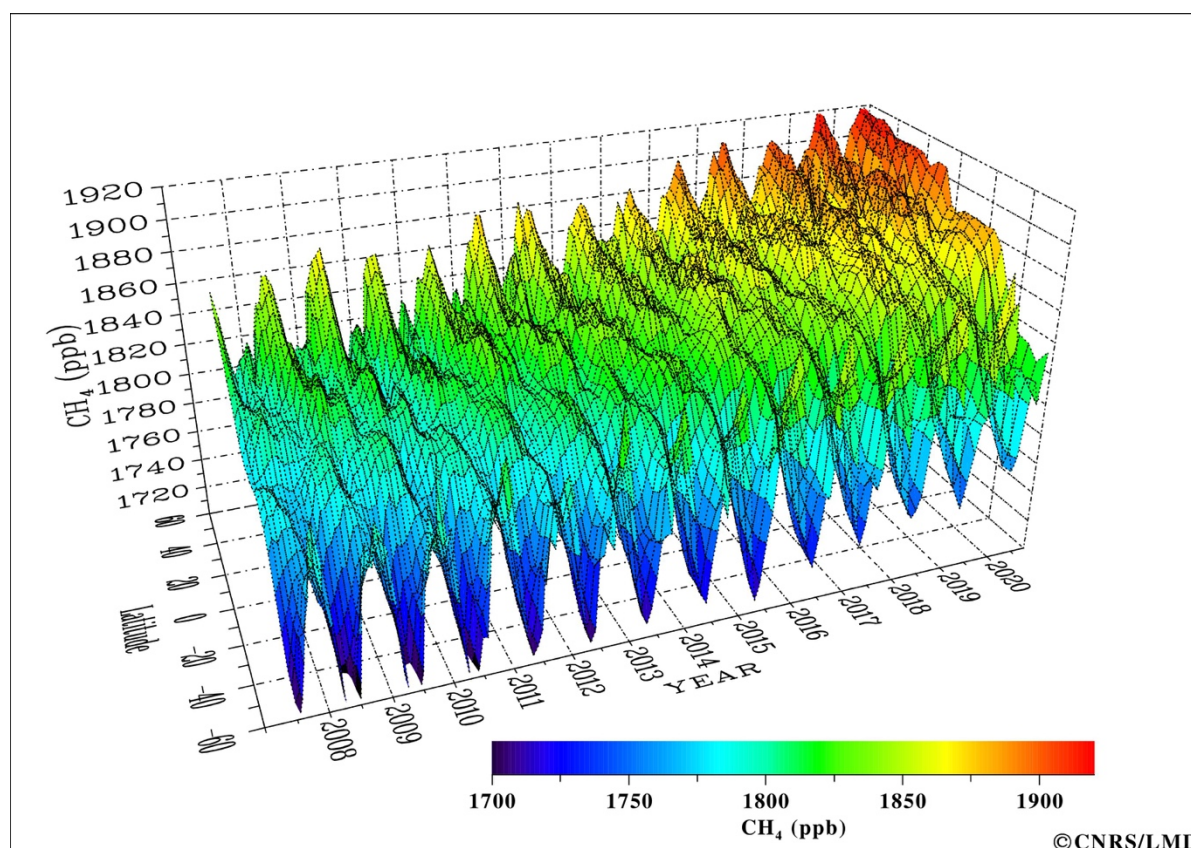


Figure 5. Monthly evolution displayed as a function of latitude of CH₄ mid-tropospheric column averaged mole fraction retrieved from Metop-A and Metop-B combined (version 9.1).



1.3 AIRS CO₂ mid-tropospheric column averaged mole fractions

Also described in this document is the Level 2 mid-tropospheric column averaged mole fractions retrieved from simultaneous observations of the AIRS and AMSU instruments flying together onboard the Aqua satellite since 2002 using a non-linear inference scheme (*Crevoisier et al., 2003*). This dataset covers the period January 2003-June 2006. Although AIRS is still in operation, the loss of several channels that were used in the retrieval has stopped the generation of retrievals. As part of C3S, the dataset generated during the ESA-CCI-GHG initiative has been rewritten in daily netcdf files, following the same structure as for the other products.



2. Target requirements

Quality requirements for Level 2 products generated from IASI and delivered to C3S are discussed in the Target Requirements Document (TRD) (D2). Table 1 shows the random and systematic errors stated in the TRD. The evaluation itself of our products is described in the PQAR document (D3).

Table 1: Mid/upper tropospheric CO₂ and CH₄ random ("precision") and systematic retrieval error requirements. Abbreviations: G=Goal, B=Breakthrough, T=Threshold requirement. §) Required systematic error after an empirical bias correction, that does not use the verification data. #) Required systematic error and stability after bias correction, where bias correction is not limited to the application of a constant offset / scaling factor.

Random and systematic error requirements for mid/upper tropospheric CO ₂ and CH ₄					
Parameter	Req. type	Random error ("Precision")		Systematic error	Stability
		Single obs.	1000 ² km ² monthly		
CO ₂	G	< 1 ppm	< 0.3 ppm	< 0.2 ppm (absolute)	As systematic error but per year
	B	< 3 ppm	< 1.0 ppm	< 0.3 ppm (relative §)	-"-
	T	< 8 ppm	< 1.3 ppm	< 0.5 ppm (relative #)	-"-
CH ₄	G	< 9 ppb	< 3 ppb	< 1 ppb (absolute)	< 1 ppb/year (absolute)
	B	< 17 ppb	< 5 ppb	< 5 ppb (relative §)	< 2 ppb/year (relative §)
	T	< 34 ppb	< 11 ppb	< 10 ppb (relative #)	< 3 ppb/year (relative #)



3. Data usage information

3.1 Product content and format

The daily Netcdf files contain all of the common parameters for the C3S data products. The mid-tropospheric column averaged mole fractions of CH₄ (ppb) and CO₂ (ppm) are stored in the ch4 and co2 variables. The quality flags (0=good) must be applied before use. Averaging kernels are provided on pressure layers (pressure-weight), as opposed to layers. A dimension of *n* refers to the number of retrievals per file. A dimension of *m* refers to the number of levels used in the radiative transfer retrieval process.

Table 2: Variables present in the Netcdf file for the CH4_IASA_NLIS and CH4_IASB_NLIS products.

Name	Type	Dimension	Units	Description
latitude	float	n	degrees_north	Center latitude of the measurement
longitude	float	n	degrees_east	Center longitude of the measurement
time	float	n	seconds since 1970-1-1 0:0:0	Measurement time
solar_zenith_angle	float	n	degrees	Angle between line of sight to the sun and local vertical
sensor_zenith_angle	float	n	degrees	Angle between the line of sight to the sensor and the local vertical
ch4_quality_flag	byte	n		0=good, 1=bad
ch4	float	n	1e-9	Retrieved mid-tropospheric column of atmospheric methane (CH ₄) in ppb
ch4_uncertainty	float	n	1e-9	1-sigma uncertainty of the retrieved Mid-tropospheric-CH ₄ in ppb
ch4_averaging_kernel	float	n, m		Normalized column-averaging kernel, which represents the sensitivity of the retrieved mid-tropospheric CH ₄ to the atmospheric methane mole fraction depending on pressure (height). All values represent layer averages within the corresponding pressure levels.
pressure_levels	float	n, m	hPa	Pressure levels define the boundaries of the averaging kernel. Surface pressure is represented by the 1st element, i.e., profiles are ordered from surface to top of atmosphere.
pressure_weight	float	n, m	hPa	Layer dependent weights corresponding to pressure levels



Table 3: Variables present in the Netcdf file for the CO2_IASA_NLIS, CO2_IASB_NLIS and CO2_AIRS_NLIS products.

Name	Type	Dimension	Units	Description
latitude	float	n	degrees_north	Center latitude of the measurement
longitude	float	n	degrees_east	Center longitude of the measurement
time	float	n	seconds since 1970-1-1 0:0:0	Measurement time
solar_zenith_angle	float	n	degrees	Angle between line of sight to the sun and local vertical
sensor_zenith_angle	float	n	degrees	Angle between the line of sight to the sensor and the local vertical
co2_quality_flag	byte	n		0=good, 1=bad
co2	float	n	1e-6	Retrieved mid-tropospheric column of atmospheric methane (CO ₂) in ppm
co2_uncertainty	float	n	1e-6	1-sigma uncertainty of the retrieved Mid-tropospheric-CO ₂ in ppm
co2_averaging_kernel	float	n, m		Normalized column-averaging kernel, which represents the sensitivity of the retrieved mid-tropospheric CO ₂ to the atmospheric methane mole fraction depending on pressure (height). All values represent layer averages within the corresponding pressure levels.
pressure_levels	float	n, m	hPa	Pressure levels define the boundaries of the averaging kernel. Surface pressure is represented by the 1st element, i.e., profiles are ordered from surface to top of atmosphere.
pressure_weight	float	n, m	hPa	Layer dependent weights corresponding to pressure levels

3.2 Tools for reading data

Data are provided in Netcdf files that can easily be read with standard tools in any common programming languages.



3.3 Recommended data usage

For model comparison or for intercomparison with in-situ or remote-sensing measurements for which vertical profile information is available, use should be made of the provided normalized-column averaging kernels, denoted G . The 40 G_i values are independent of the layer thickness and can be interpolated to any vertical layer distribution. Note that they are normalized so that the sum of the G_i , weighted by layer pressure thickness, is 1. The simulated integrated content of the consider gas, denoted q_{gas}^{other} , is finally given by

$$q_{gas}^{other} = \frac{\sum_{i=1}^{M_{lay}} H_i \Delta p_i q_i}{\sum_{i=1}^{M_{lay}} H_i \Delta p_i}$$

where H_i is the vertical weighting function G_i interpolated on the M_{lay} pressure layers Δp_i used by the other product for which the gas mixing ratio q_i at level P_i is given in ppb.

3.4 Known limitations and issues

- From beginning of 2015, AMSU channel 7 has started degrading and then exceeding specifications. Retrievals performed from IASI/AMSU onboard Metop-A have thus been stopped in August 2015, and more ‘bad quality’ retrievals have been flagged in the first half of 2015 than the years before. The regeneration of the full dataset without the information given by AMSU7 is planned for the next release.
- For high scan angles (between 10th and 15th angle), the retrievals display a variation with the scan angle that depends on the year, and that can reach quite high values at the edges of the orbits. For these reasons, only retrievals for scan angles lower than the 10th angle are provided.
- A 2 ppm bias was found in CO₂ retrieved from Metop-B with version V4.1. An update of the computation of radiative biases characterizing IASI and AMSU Metop-B channels has been removed it in version V4.2.
- Differences in CO₂ partial columns (v9.1) larger than 2 ppm have been observed between Metop-A and Metop-B for latitudes higher than 25°N/S larger.
- Differences in CH₄ partial columns (v9.1) larger than 10 ppb have been observed between Metop-A and Metop-B for latitudes higher than 60°N/S larger.
- A 1ppm bias is found in CO₂ retrieved from Metop-A with version 9.1 from the last months of 2019. This is linked to a change in the correction of the detectors non linearity on Metop-A by the end of 2019. This change at instrument level has impacted the radiances themselves in the longwave band of IASI spectrum where the CO₂ absorption bands are located. The full characterization of this change is on-going. Once the impact has been properly characterized at Level 1, a correction of the radiances will be made and taken into account in the retrieval process.



References

- 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, <http://dx.doi.org/10.1016/j.rse.2013.04.024>, 2015.
- Crevoisier et al., 2003:** Crevoisier, C., Chedin, A. and Scott, N.A., AIRS channel selection for CO₂ and other trace-gas retrievals 129, 2719–2740. doi:10.1256/qj.02.180, 2003.
- 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., 2009a:** 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.
- ESA-CCI-GHG-URDv3.0:** Chevallier, F., et al., User Requirements Document (URD), ESA Climate Change Initiative (CCI) GHG-CCI project, Version 3.0, 17 Feb 2020, pp. 42, link: https://www.iup.uni-bremen.de/carbon_ghg/docs/GHG-CCIplus/URD/URDv3.0_GHG-CCIp_Final.pdf, 2020.
- 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_10oct2016.pdf, 2016.



Jacquinet-Husson et al., 2011: Jacquinet-Husson, N., Crepeau, L., Armante, R., et al. (2011). The 2009 edition of the GEISA spectroscopic database. *J. Quant. Spectrosc. Radiat. Transf.* 112, 2395–2445. doi:10.1016/j.jqsrt.2011.06.004.

Scott and Chédin, 1981: Scott, N.A. and Chédin, A., A Fast Line-by-Line Method for Atmospheric Absorption Computations: The Automatized Atmospheric Absorption Atlas. *J. Appl. Meteorol.* 20, 802–812. doi:10.1175/1520-0450(1981)020<0802:AFLBLM>2.0.CO;2, 1981.

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, 28-March-2017, pp. 52, 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.

Copernicus Climate Change Service

ECMWF - Shinfield Park, Reading RG2 9AX, UK

Contact: info@copernicus-climate.eu

climate.copernicus.eu

copernicus.eu

ecmwf.int