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Satellite-based atmospheric CO_2 dataset

Deliverable D1.5

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About 4C

Climate-Carbon Interactions in the Coming Century (4C) is an EU-funded H2020 project that addresses the crucial knowledge gap in the climate sensitivity to carbon dioxide emissions, by reducing the uncertainty in our quantitative understanding of carbon-climate interactions and feedbacks. This will be achieved through innovative integration of models and observations, providing new constraints on modelled carbon-climate interactions and climate projections, and supporting Intergovernmental Panel on Climate Change (IPCC) assessments and policy objectives.

1 Executive Summary

This deliverable describes an atmospheric carbon dioxide (CO_2) data set derived from satellite observations of radiance spectra of solar radiation reflected by the Earth's surface in the near-infrared/shortwave-infrared spectral region. We present data product XCO2_OBS4MIPS_2x2. XCO_2 is the column-averaged dry-air mole fraction of atmospheric CO2, OBS4MIPS refers to the Obs4MIPs data format, and 2x2 refers to the spatial resolution of the data product (regular 2° latitude times 2° longitude grid). The temporal resolution is monthly. This data product has been generated by gridding (averaging) the multi-satellite / multi-algorithm merged EMMA v4.2 XCO_2 data product, where EMMA refers to the Ensemble Median Algorithm. The ensemble of input data consists of several XCO_2 data sets as derived from the satellite sensors SCIAMACHY/ENVISAT (2003-2012), Tanso-FTS/GOSAT (since 2009) and OCO-2 (since 2014). The XCO2_OBS4MIPS_2x2 v4.2 data product covers the time period January 2003 to December 2019. It is shown in this document that the characteristics of the product depends on time (especially the spatial coverage) due to the characteristic of the underlying input satellite data used to generate the merged XCO2_OBS4MIPS_2x2 data product. It is also shown that the spatial coverage is quite sparse due to strict quality filtering (required, e.g., to avoid biases due to cloud contamination). Product XCO2_OBS4MIPS_2x2 has been compared with ground-based Total Carbon Column Observing Network (TCCON) XCO_2 retrievals. The validation results can be summarized as follows: Overall bias: -0.1 ppm (slight low bias), scatter (1-sigma): 1.34 ppm, the (linear) correlation with TCCON is 0.99, i.e., very good. No significant linear bias drift has been identified (-0.09 ± 0.21 ppm/year), i.e., the product is very stable. The data product presented in this deliverable report is freely accessible (see respective "data availability" section) and serves as a novel constraint for the partner work packages within the 4C project. An earlier version of this data product has already been used within 4C for this purpose.

Keywords

2 Satellite-based atmospheric CO_2 dataset (XCO2_OBS4MIPS_2x2, version 4.2)

2.1 Overview

We present the satellite-derived data product XCO2_OBS4MIPS_2x2. XCO_2 is the column-averaged dry-air mole fraction of atmospheric CO_2, OBS4MIPS refers to the Obs4MIPs data format, and 2x2 to the spatial resolution of the data product (regular 2° latitude times 2° longitude grid). The temporal resolution is monthly.

This data product has been generated by gridding (averaging) the multi-satellite / multi-algorithm merged EMMA v4.2 XCO_2 data product, where EMMA refers to the Ensemble Median Algorithm **/Reuter et al., 2013, 2020a/**.

In this document only a short overview about product XCO2_OBS4MIPS_2x2 is given. Details on input data sets, the EMMA method and the validation method are given in **/Reuter et al., 2020a-d/**.

In **/Reuter et al., 2020b-d/**, the generation of the EMMA v4.2 input data set is described and how it has been used to generate an XCO_2 product in Obs4MIPs format at 5°x5° resolution. The product described in this document, i.e., product XCO2_OBS4MIPS_2x2, is essentially identical with the 5°x5° resolution product, except for the higher spatial resolution (2°x2°) of product XCO2_OBS4MIPS_2x2.

The XCO2_OBS4MIPS_2x2 v4.2 data product covers the time period January 2003 to December 2019.

It is shown in this document that the characteristics of the product depends on time (especially the spatial coverage) due to the characteristic of the underlying input satellite data used to generate the merged XCO2_OBS4MIPS_2x2 data product. It is also shown that the spatial coverage is quite sparse due to strict quality filtering (required, e.g., to avoid biases due to cloud contamination)

Product XCO2_OBS4MIPS_2x2 has been compared with ground-based Total Carbon Column Observing Network (TCCON) XCO_2 retrievals. The validation results can be summarized as follows: Overall bias: -0.1 ppm (slight low bias), scatter (1-sigma): 1.34 ppm (contributions: random and systematic errors of the satellite data, representation error, TCCON errors, …), the (linear) correlation with TCCON is 0.99, i.e., very good. No significant linear bias drift has been identified (-0.09 ± 0.21 ppm/year), i.e., the product is very stable.

2.2 Input data

The XCO2_OBS4MIPS_2x2 v4.2 data product has been obtained by gridding (averaging) the XCO2_EMMA v4.2 XCO_2 data product.

The EMMA product and its validation is described in detail in **/Reuter et al., 2020b-d/**.

In short, the EMMA product is a Level 2 data product containing for each satellite footprint (i.e., single observation) detailed information on geolocation (latitude, longitude), time, XCO_2, XCO_2 uncertainty, XCO_2 averaging kernel, etc. The EMMA product has been generated using an ensemble of individual satellite sensor data products, i.e., the EMMA product is a multi-sensor / multi-algorithm merged data product. The satellite sensors are (see also **/Reuter et al., 2020a/** for details):

- SCIAMACHY / ENVISAT (ESA; 2003-2012)
- TANSO-FTS / GOSAT (JAXA/NIES, since 2009)
- OCO-2 (NASA, since 2014)

2.3 Algorithm

The algorithm which has been used to generate the XCO2_OBS4MIPS_2x2 v4.2 data product is the same algorithm as has also been used to generate the XCO2_OBS4MIPSv4.2 data product **/Reuter et al., 2020b/**, which has a spatial resolution of 5°x5°.

2.4 Product description

Product XCO2_OBS4MIPS_2x2 v4.2 consists of a single NetCDF file:

xco2_c3s_l3_v42_200301_201912_2x2.nc (size: 310 MB)

The product is self-explaining as it contains all relevant information (description of all variables incl. corresponding units, etc.). A detailed product description including product format is given in **/Reuter et al., 2020d/.**

2.5 Maps and time series

In this section, we show how product XCO2_OBS4MIPS_2x2 “looks like”.

Figure 1 presents an overview about this product in terms of time series and spatial maps. As can be seen, XCO_2 increases with time (primarily due to burning of fossil fuels) and shows a seasonal cycle, especially over the northern hemisphere (primarily due to uptake and release of atmospheric CO_2 by terrestrial vegetation).

As can be seen from the spatial maps, the spatial coverage depends on time. This is due to the different characteristics of the underlying satellite data (see, e.g., **/Reuter et al., 2020a/** for details).

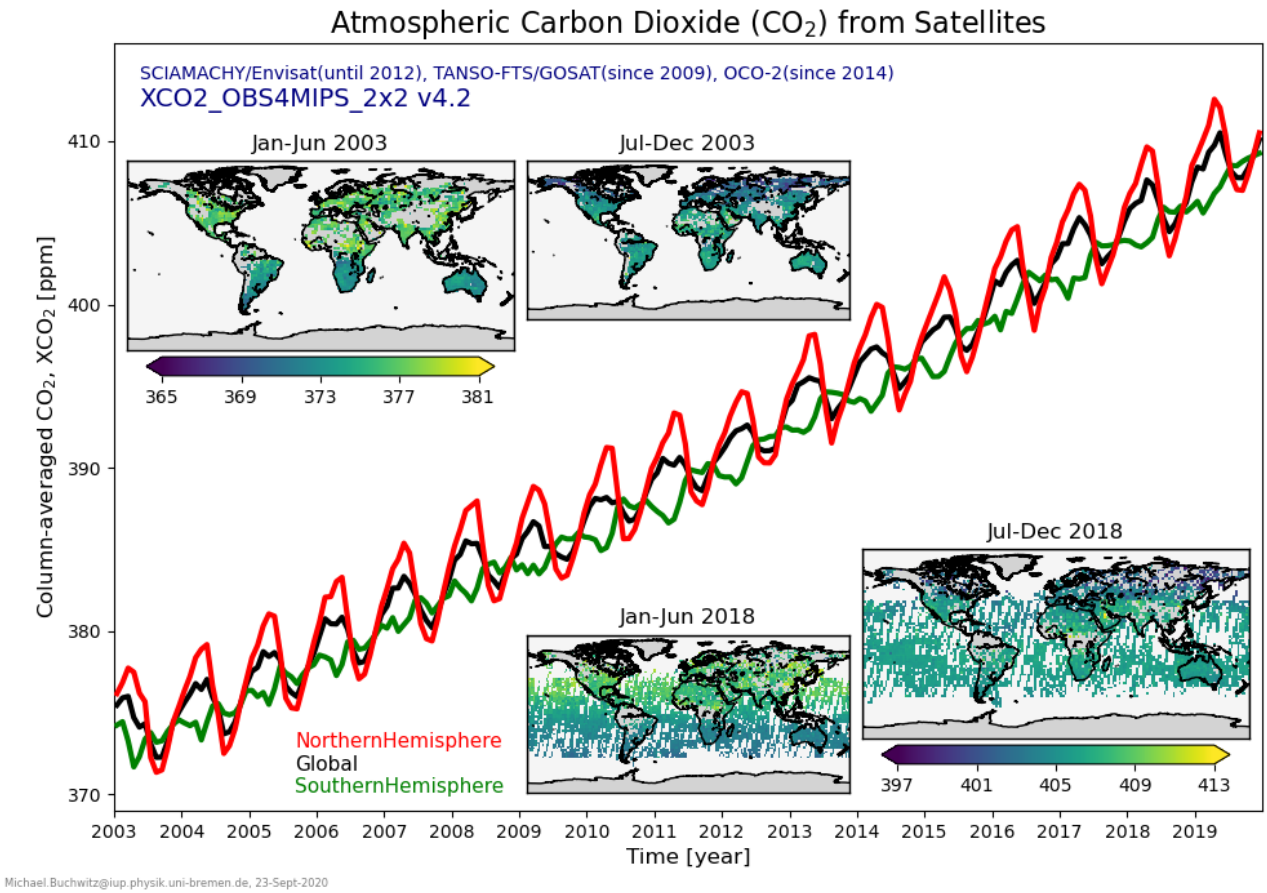


Figure 1: Overview of product XCO2_OBS4MIPS_2x2 in terms of time series for three latitude bands and half-yearly global maps..

Figure 2 (a) to (d) shows XCO_2 and related quantities for August in different years: (a) 2003, (b) 2010, (c) 2013, (d) 2019. The top left maps show XCO_2, the top right maps show the (reported) XCO_2 uncertainty (1-sigma; standard error), the bottom left maps show the number of observations per $2^o x 2^o$ grid cell and the bottom right maps show the standard deviation of the (input) Level 2 observations within each grid cell. (b) to (d): as (a) but for 2010, 2013, 2019.

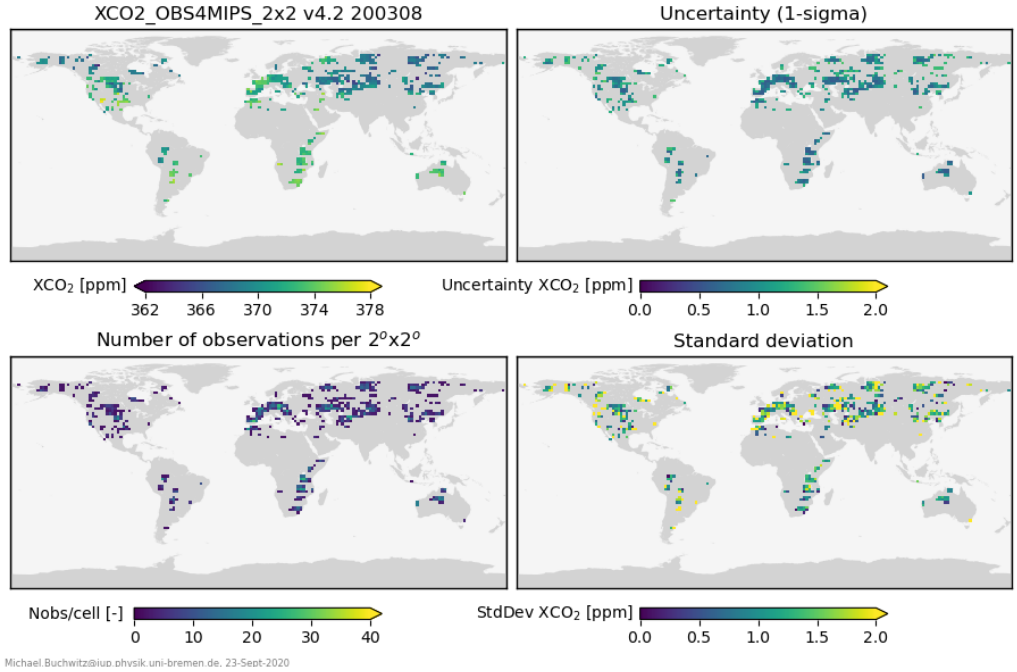
Figure 2 (a) shows the data product for August 2003. This part of the product is only based on a single XCO_2 data product from one satellite instrument, namely SCIAMACHY on ENVISAT, retrieved using the BESD algorithm (see **/Reuter et al., 2020a/** for details). Data coverage is limited to observations over land.

Figure 2 (b) is shows the data product for August 2010. Here in addition to the SCIAMACHY/BESD product an ensemble of GOSAT product has been used in addition (see **/Reuter et al., 2020a/** for details). As can be seen, there is now also some ocean coverage.

Figure 2 (c) is shows the data product for August 2013, based on an ensemble of GOSAT products (see **/Reuter et al., 2020a/** for details).

Figure 2 (d) is shows the data product for August 2019, based on an ensemble of GOSAT and OCO-2 products (see **/Reuter et al., 2020a/** for details).

(a)



(b)

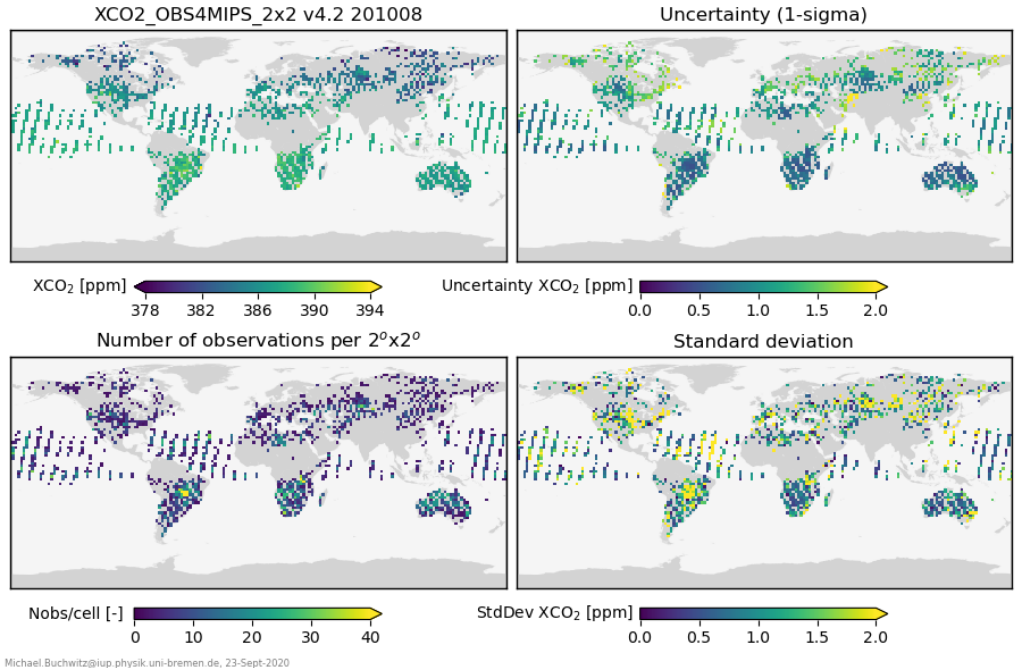
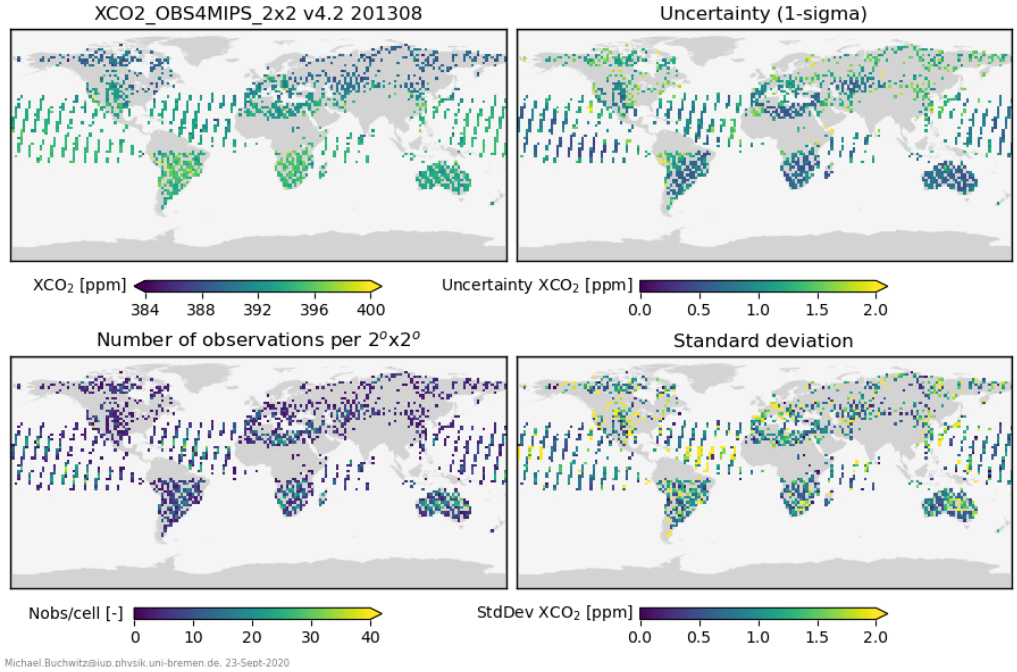


Figure continued on next page.

(c)



(d)

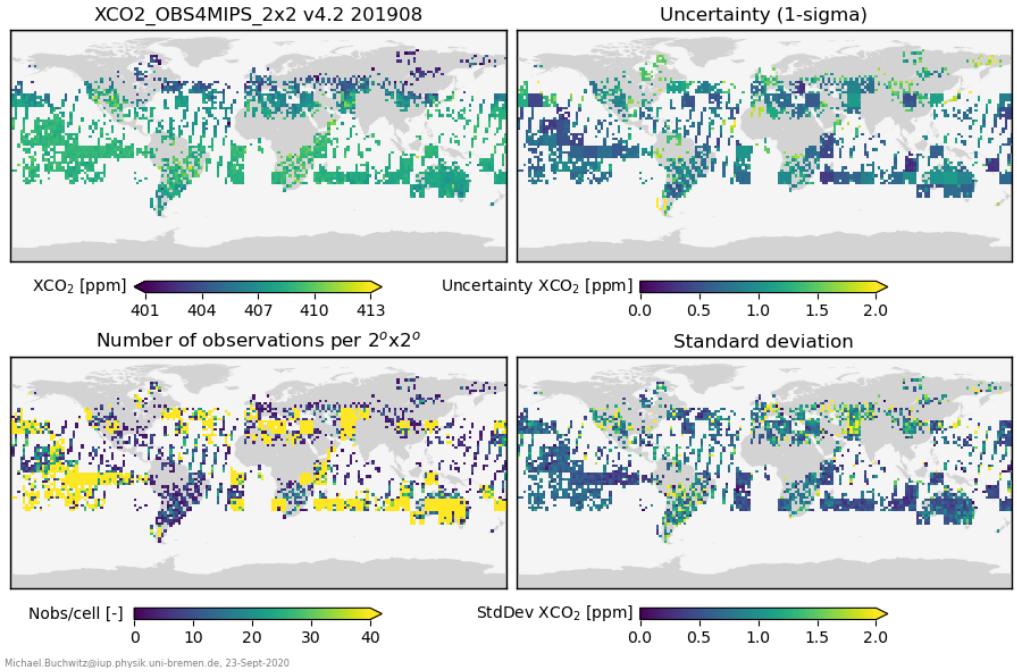


Figure 2: (a) XCO_2 and related quantities for August 2002. Top left: XCO_2. Top right: XCO_2 uncertainty (1-sigma; standard error). Bottom left: Number of observations per 2°x2° grid cell. Bottom right: standard deviation of the (input) Level 2 observations within each grid cell. (b) to (d): as (a) but for 2010, 2013, 2019.

2.6 Validation

Product XCO2_OBS4MIPS_2x2 has been compared with ground-based Total Carbon Column Observing Network (TCCON) XCO_2 retrievals **/Wunch et al., 2011/**. The overall validation results are shown in Fig. 3. The validation method is explained in **/Reuter et al., 2020a/**.

The validation results can be summarized as follows: Overall bias: -0.1 ppm (slight low bias), scatter (1-sigma): 1.34 ppm, correlation with TCCON: 0.99. No significant linear bias drift has been identified (-0.09 ± 0.21 ppm/year), i.e., the product is very stable.

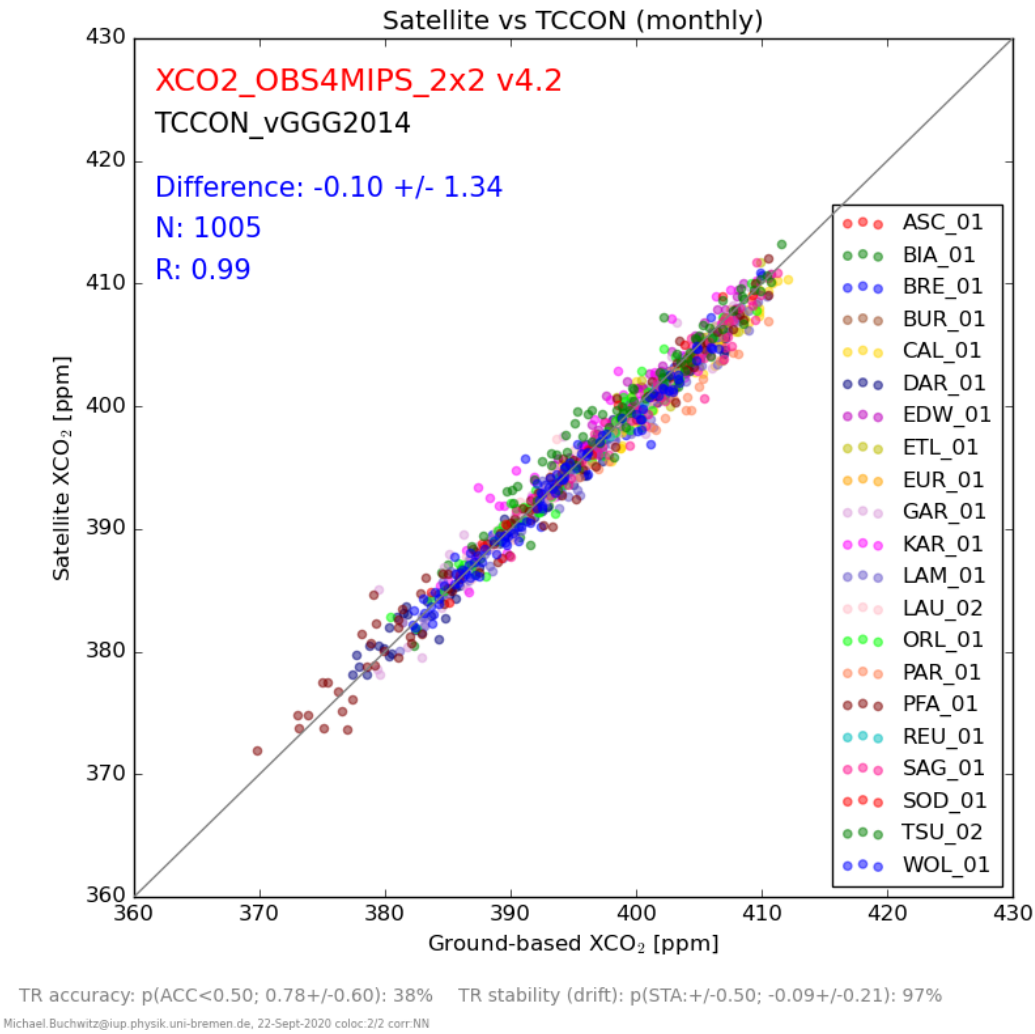


Figure 3: Validation of product XCO2_OBS4MIPS_2x2 version 4.2 by comparison with TCCON ground-based XCO2 observations. Each symbol denotes a comparison of a monthly value at a given TCCON sites (N = 1005 combinations; each color corresponds to a certain TCCON sites; the used TCCON sites are listed on the right hand side).

2.7 Data availability

Access and use of data product XCO2_OBS4MIPS_2x2 version 4.2 does not require registration and is free of charge. However, if the data product is used for any type of presentation or publication it is required to add the following acknowledgement:

“The XCO2_OBS4MIPS_2x2 version 4.2 data product has been generated by University of Bremen using funding from the European Commission H2020 project 4C (Climate-Carbon Interactions in the Current Century, Grant Agreement No. 821003).”

Information about the underlying satellite Level 2 input data and the generation of a corresponding XCO2_OBS4MIP at 5°x5° resolution can be obtained from this peer-reviewed publication:

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., Notholt, J., Petri, C., Warneke, T., Velazco, V., Deutscher, N. M., Griffith, D. W. T., Kivi, R., Pollard, D., 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., 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.

Data product XCO2_OBS4MIPS_2x2 version 4.2 can be downloaded from here (single NetCDF file, 310 MB):

https://www.iup.uni-bremen.de/carbon_ghg/data/xco2_c3s_l3_v42_200301_201912_2x2.nc

2.8 Acknowledgements

This research has received funding from the European Union (EU) Horizon 2020 (H2020) research and innovation programme project 4C (formerly CCiCC) grant agreement number 821003.

The generation of the presented satellite data product and its validation would not have been possible without the availability of several input data sets and funding from other projects and agencies: The generation of the EMMA Level 2 input data set and the corresponding data analysis has been funded primarily by the EU via the Copernicus Climate Change Service (C3S, https://climate.copernicus.eu/) managed by the European Centre for Medium-range Weather Forecasts (ECMWF). That work strongly benefited from additional funding by the European Space Agency (ESA) via ESA's Climate Change Initiative (CCI, http://www.esa-ghg-cci.org/) projects GHG-CCI/GHG-CCI+. The further development of the FOCAL retrieval algorithm used to generate the OCO-2/FOCAL XCO2 input data product would not have been possible without co-funding from the EU H2020 projects CHE (Grant Agreement No. 776186) and VERIFY (Grant Agreement No. 776810). We thank several space agencies for making available satellite Level 1 (L1) input data: ESA/DLR for SCIAMACHY L1 data, JAXA for GOSAT Level 1B data and NASA for the OCO-2 L1 data product. We also thank ESA for making the GOSAT L1 product available via the ESA Third Party Mission (TPM) archive. We thank NIES for the operational GOSAT XCO2 and XCH4 Level 2 products and the NASA team for the GOSAT and OCO-2 ACOS Level 2 XCO2 products. TCCON data were obtained from the TCCON Data Archive, hosted by CaltechDATA, California Institute of Technology (https://tccondata.org/). The TCCON stations Ascension Island, Bremen, Garmisch, Karlsruhe and Ny-Ålesund have been supported by the German Bundesministerium für Wirtschaft und Energie (BMWi) via DLR under grants 50EE1711A-E. We thank the ESA Ariane Tracking Station at North East Bay, Ascension Island, for hosting and local support. N.M.D. is supported by an ARC Future Fellowship, FT180100327. The TCCON site at Réunion Island is operated by the Royal Belgian Institute for Space Aeronomy with financial support in 2014, 2015, 2016, 2017, 2018 and 2019 under the EU project ICOS-Inwire and the ministerial decree for ICOS (FR/35/IC2) and local activities supported by LACy/UMR8105 – Université de La Réunion.

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