



# **Product Quality Assessment Report (PQAR) – ANNEX B for products CO2\_GO2\_SRFP, CH4\_GO2\_SRFP (v2.0.0, 2019-2021)**

## **C3S2\_312a\_Lot2\_DLR – Atmosphere**

Issued by: Andrew Barr and Tobias Borsdorff, SRON, The Netherlands

Date: 02/03/2023

Ref: C3S2\_312a\_Lot2\_D-WP2\_PQAR-2022-GHG\_ANNEX-B\_v6.3

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

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

T. Borsdorff

A. G. Barr

O. P. Hasekamp



## History of modifications

Version	Date	Description of modification	Chapters / Sections
1.1	20-October-2017	New document for data set CDR1 (2009-2016)	All
2.0	4-October-2018	Update for CDR2 (2009-2017)	All
3.0	12-August-2019	Update for CDR3 (2009-2018)	All
3.1	03-November-2019	Update after review by Assimila: Primarily correction of typos.	All
4.0	18-August-2020	Update for CDR4 (2009-2019)	All
5.0 beta	18-February-2021	Update for CDR5 (2009-mid2020)	All
5.0	23-April-2021	Improvements after review by Assimila (formatting issues)	All
6.0	04-August-2022	Update for CDR6: GOSAT-2 retrievals (2019 – 2021)	All
6.1	14-December-2022	Update after review (use of new template, several improvements at various places)	All
6.2	30-January-2023	Update after 2 <sup>nd</sup> review. Several improvements at various places.	All
6.3	02-March-2023	Minor update after 2 <sup>nd</sup> review to generate clean version.	All

## List of datasets covered by this document

Deliverable ID	Product title	Product type (CDR, ICDR)	Version number	Delivery date
WP2-FDDP-GHG-v1	CO2_GO2_SRFP	CDR 6	2.0.0	31-Aug-2022
WP2-FDDP-GHG-v1	CH4_GO2_SRFP	CDR 6	2.0.0	31-Aug-2022



## Related documents

Reference ID	Document
D1	<p>Main PQAR:</p> <p>Buchwitz, M., et al., Product Quality Assessment Report (PQAR) – Main document for Greenhouse Gas (GHG: CO<sub>2</sub> &amp; CH<sub>4</sub>) data set CDR 6 (2003-2021), project C3S2_312a_Lot2_DLR – Atmosphere, v6.3, 2023.</p> <p><b>Important Note:</b></p> <p><i>This document is an ANNEX to the Main PQAR document and contains the quality assessment results of the data provider.</i></p> <p><b><i>For the final overall quality assessment results of the data products described in this document see the Main PQAR document.</i></b></p>
D2	<p>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 (CO<sub>2</sub> and CH<sub>4</sub>) data products (project C3S_312a_Lot6), Version 1, 28-March-2017, pp. 52, 2017.</p>



## Acronyms

Acronym	Definition
ATBD	Algorithm Theoretical Basis Document
CAR	Climate Assessment Report
C3S	Copernicus Climate Change Service
CCI	Climate Change Initiative
CDR	Climate Data Record
CDS	(Copernicus) Climate Data Store
CRG	Climate Research Group
D/B	Data base
EC	European Commission
ECMWF	European Centre for Medium Range Weather Forecasting
ECV	Essential Climate Variable
EO	Earth Observation
ESA	European Space Agency
EU	European Union
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FP	Full Physics retrieval method
FTIR	Fourier Transform InfraRed
FTS	Fourier Transform Spectrometer
GCOS	Global Climate Observing System
GEOSS	Global Earth Observation System of Systems
GHG	GreenHouse Gas
GOSAT	Greenhouse Gases Observing Satellite
GOSAT-2	Greenhouse Gases Observing Satellite 2
IPCC	International Panel in Climate Change
IUP	Institute of Environmental Physics (IUP) of the University of Bremen, Germany
JAXA	Japan Aerospace Exploration Agency
KIT	Karlsruhe Institute of Technology
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
NetCDF	Network Common Data Format
NIES	National Institute for Environmental Studies



NIR	Near Infra Red
NOAA	National Oceanic and Atmospheric Administration
Obs4MIPs	Observations for Climate Model Intercomparisons
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
RemoTeC	Retrieval algorithm developed by SRON
REQ	Requirement
RMS	Root-Mean-Square
RTM	Radiative transfer model
SNR	Signal-to-Noise Ratio
SRON	SRON Netherlands Institute for Space Research
SWIR	Short Wave Infra Red
SZA	Solar Zenith Angle
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
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.

### 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.

### 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).

### Intermediate climate data record (ICDR)

An intermediate climate data record (ICDR) is a TCDR which undergoes regular and consistent updates, 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.

- 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., XCO<sub>2</sub>) 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)





Additional definitions as relevant for this document:

In the following some relevant Target Requirement (TR) related definitions are given. For details please see *TRD (D2), 2017*, *ESA-CCI-GHG-URDv2.1* and *CMUG-RBD, 2010*:

**Systematic error**: component of measurement error that in replicate measurements remains constant or varies in a predictable manner

Note: “Systematic error” = “Absolute systematic error” (in contrast to “Relative systematic error” defined below).

For satellite GHG ECV products especially the “Relative systematic error” is important. The definition as used here is as follows:

**Relative systematic error**: Identical with “Systematic error” but after bias correction and without considering a possible “global offset” (overall mean bias). Reflects the importance of spatially and temporally correlated errors (“spatio-temporal biases”). Computed from standard deviations of spatial and temporal biases.

**Bias**: estimate of a systematic measurement error (*JCGM, 2008*).

**Precision** is the measure of reproducibility or repeatability of the measurement without reference to an international standard so that precision is a measure of the random and not the systematic error. Suitable averaging of the random error can improve the precision of the measurement but does not establish the systematic error of the observation (*CMUG-RBD, 2010*).

Note: Precision (as explained in *TRD (D2)*) is quantified with the standard deviation (1-sigma) of the error distribution.

**Stability** is a term often invoked with respect to long-term records when no absolute standard is available to quantitatively establish the systematic error - the bias defining the time-dependent (or instrument-dependent) difference between the observed quantity and the true value (*CMUG-RBD, 2010*).

Note: Stability requirements cover inter-annual error changes. If the change in the average bias from one year to another is larger than the defined values, the corresponding product does not meet the stability requirement.

Representativity is important when comparing with or assimilating in models. Measurements are typically averaged over different horizontal and vertical scales compared to model fields. If the measurements are smaller scale than the model it is important. The sampling strategy can also affect this term (*CMUG-RBD, 2010*).



**Threshold requirement:** The threshold is the limit at which the observation becomes ineffectual and is not of use for climate-related applications (*CMUG-RBD, 2010*).

**Goal requirement:** The goal is an ideal requirement above which further improvements are not necessary (*CMUG-RBD, 2010*).

**Breakthrough requirement:** The breakthrough is an intermediate level between the “threshold” and “goal” requirements, which - if achieved - would result in a significant improvement for the targeted application. The breakthrough level may be considered as an optimum, from a cost-benefit point of view when planning or designing observing systems (*CMUG-RBD, 2010*).

**Horizontal resolution** is the area over which one value of the variable is representative of (*CMUG-RBD, 2010*).

**Vertical resolution** is the height over which one value of the variable is representative of. Only used for profile data (*CMUG-RBD, 2010*).

**Observing Cycle** is the temporal frequency at which the measurements are required (*CMUG-RBD, 2010*).

Note: In this document also the term “Revisit time” may be used. The definition is identical with the definition of “Observing cycle”. Both terms refer to the (average) temporal frequency at a given location.



## Table of Contents

<b>History of modifications</b>	<b>4</b>
<b>List of datasets covered by this document</b>	<b>4</b>
<b>Related documents</b>	<b>5</b>
<b>Acronyms</b>	<b>6</b>
<b>General definitions</b>	<b>8</b>
<b>Scope of document</b>	<b>12</b>
<b>Executive summary</b>	<b>13</b>
<b>1. Product validation methodology</b>	<b>14</b>
1.1 Co-location method	14
<b>2. Validation Results</b>	<b>15</b>
<b>2.1 Product CO<sub>2</sub>_GO<sub>2</sub>_SRFP</b>	<b>15</b>
2.1.1 Validation	15
2.1.2 Stability	19
2.1.3 Validation summary	23
2.1.4 GOSAT-GOSAT2 Intercomparison	24
<b>2.2 Product CH<sub>4</sub>_GO<sub>2</sub>_SRFP</b>	<b>27</b>
2.2.1 Validation	27
2.2.2 Stability	31
2.2.3 Validation summary	35
2.2.4 GOSAT-GOSAT2 Intercomparison	36
<b>3. Application(s) specific assessments</b>	<b>39</b>
<b>4. Compliance with user requirements</b>	<b>39</b>
<b>References</b>	<b>40</b>



## Scope of document

This document is a Product Quality Assessment Report (PQAR) for the Copernicus Climate Change Service (C3S, <https://climate.copernicus.eu/>) greenhouse gas (GHG) component as covered by project C3S2\_312a\_Lot2.

Within this project satellite-derived atmospheric carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>) Essential Climate Variable (ECV) data products will be 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 GHG satellite-derived data products are:

- Column-averaged dry-air mixing ratios (mole fractions) of CO<sub>2</sub> and CH<sub>4</sub>, denoted XCO<sub>2</sub> (in parts per million, ppm) and XCH<sub>4</sub> (in parts per billion, ppb), respectively.
- Mid/upper tropospheric mixing ratios of CO<sub>2</sub> (in ppm) and CH<sub>4</sub> (in ppb).

This document describes the validation / quality assessment of C3S2 products CO2\_GO2\_SRFP and CH4\_GO2\_SRFP v2.0.0.

These products are XCO<sub>2</sub> and XCH<sub>4</sub> Level 2 products as retrieved from GOSAT-2 using algorithms developed at SRON, The Netherlands.



## Executive summary

This report summarizes the performance of the RemoTeC CO<sub>2</sub>\_GO<sub>2</sub>\_SRFP and CH<sub>4</sub>\_GO<sub>2</sub>\_SRFP retrievals. In general, we find very good agreement with TCCON data for both modes (normal and sunglint) for both products. Both have a very high degree of correlation with TCCON ( $R \sim 0.75$ ).

For the CO<sub>2</sub>\_GO<sub>2</sub>\_SRFP product the station-to-station bias is 0.56 ppm and a standard deviation of around 2.78 ppm is observed for most TCCON stations.

For the CH<sub>4</sub>\_GO<sub>2</sub>\_SRFP product the station-to-station bias is 1.86 ppb and a standard deviation of around 17.35 ppb is observed for most TCCON stations.

We also checked the stability of the bias over time for both products as the GOSAT-2 time series spans a period of almost 3 years, and found that there has been no significant change in the bias over time, indicating a very good detector stability.

We achieved both Target Requirements (TR) for accuracy and stability for the CH<sub>4</sub>\_GO<sub>2</sub>\_SRFP product, with 99 % and 83 % of meeting the requirement, respectively, while for CO<sub>2</sub>\_GO<sub>2</sub>\_SRFP we achieved a 99 % chance that the TR is met for stability but only a 33 % chance that the TR is met for accuracy.



## 1. Product validation methodology

Validation of the CH<sub>4</sub>\_GO2\_SRFP V2.0.0 and CO<sub>2</sub>\_GO2\_SRFP V2.0.0 products is performed by comparison of the ground-based Fourier Transform Spectrometer (FTS) Total Carbon Column Observing Network (TCCON; Wunch et al. (2011, 2015)) stations in the GGG2020 TCCON release (Laughner et al. 2021). For more details see the main PQAR (D1). The TCCON data provide total column XCH<sub>4</sub> and XCO<sub>2</sub> measurements that are used to filter our retrievals and perform a bias correction of our data product. The final filtered and bias corrected product is then compared to TCCON to evaluate the global bias, accuracy and systematic biases (spatial and temporal) in the retrievals.

### 1.1 Co-location method

We co-locate the GOSAT-2 soundings with the TCCON measurements using the following criteria:

- GOSAT-2 sounding within  $\pm 5$  degree latitude and  $\pm 8$  degree longitude of TCCON station
- GOSAT-2 sounding within  $\pm 2$  hours of TCCON measurements

We then average all the TCCON measurements within  $\pm 2$  hours of a GOSAT-2 measurement to create a set of GOSAT-2-TCCON pairs. These co-located pairs are then used to perform the validation procedure.

Sunglint mode takes advantage of specific viewing angle where the radiance of back-scattered sunlight is higher due to reflection from waves. This amplifies the albedo, allowing retrievals over ocean to be carried out, where the albedo is generally too low to retrieve accurate concentrations. As a result, only TCCON stations that are close to shorelines or on islands have collocated sunglint measurements with GOSAT-2.



## 2. Validation Results

### 2.1 Product CO<sub>2</sub>\_GO2\_SRF

#### 2.1.1 Validation

Figure 1 illustrates that the normal soundings show a strong correlation of the retrieved (bias-corrected) XCO<sub>2</sub> with the TCCON XCO<sub>2</sub> ( $R = 0.74$ ). The glint soundings show a smaller correlation but that is due to the limited range of XCO<sub>2</sub> values due to the fewer TCCON stations available near to the ocean. This gives us confidence that our bias correction based on the retrieved albedo works correctly and takes out most of the bias.

Figure 2 shows in detail for each station the remaining bias and standard deviation for the co-located GOSAT-2 soundings for the period between the years 2019 to 2021. In the case of normal observations, the station-to-station standard deviation is 0.56 ppm. Caltech and Lamont have the largest number of co-locations and dominate the total statistical comparison. The largest bias is at Lauder with a remaining bias of over 1.5 ppm. The largest bias in sunglint observations is at Burgos with a bias of 1.25 ppm. For sunglint we removed Saga from the comparison as when using the static spatial co-location criterion it only had limited co-located measurements.

Figure 3 presents Hovmöller diagrams of XCO<sub>2</sub> as well as the uncertainty on this parameter, along with the number of observations across the range of GOSAT-2 observations.



Figure 1: Validation of XCO<sub>2</sub> retrieved by GOSAT-2-RemoTeC with ground based TCCON measurements for normal (top) and sunglint (bottom) soundings over the course of the full dataset (2019-2021). N indicates the number of GOSAT-2-TCCON collocations, Bias is the average difference (for individual measurements) between GOSAT-2 and TCCON, Std the standard deviation of the GOSAT-2 TCCON difference (for individual measurements) and the Pearson's correlation coefficient between the two set of observations is also given.

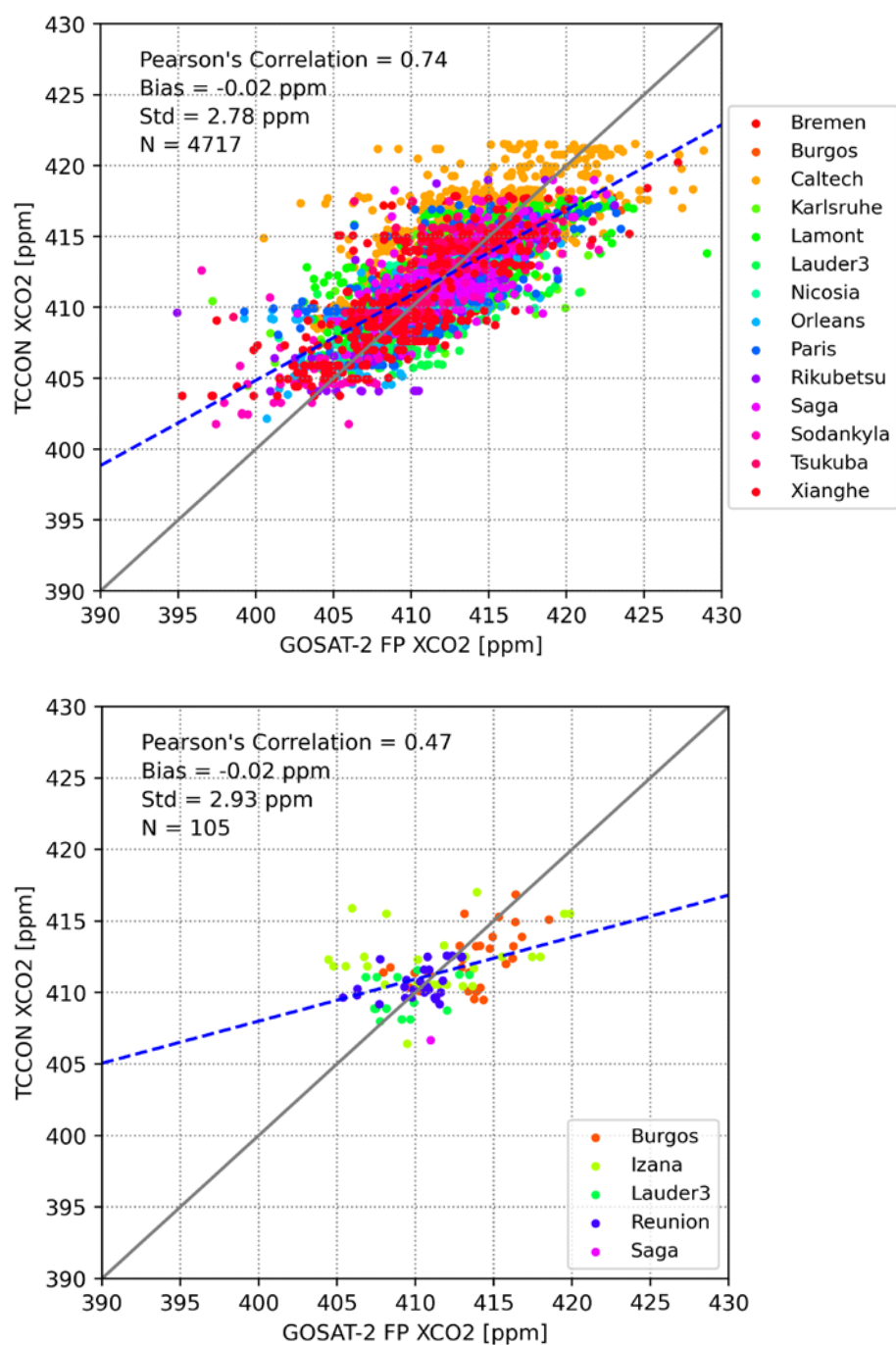






Figure 2: The bias, standard deviation and number of measurements per TCCON station for normal (left) and sunglint (right) soundings for the period between the year 2019 and 2021.

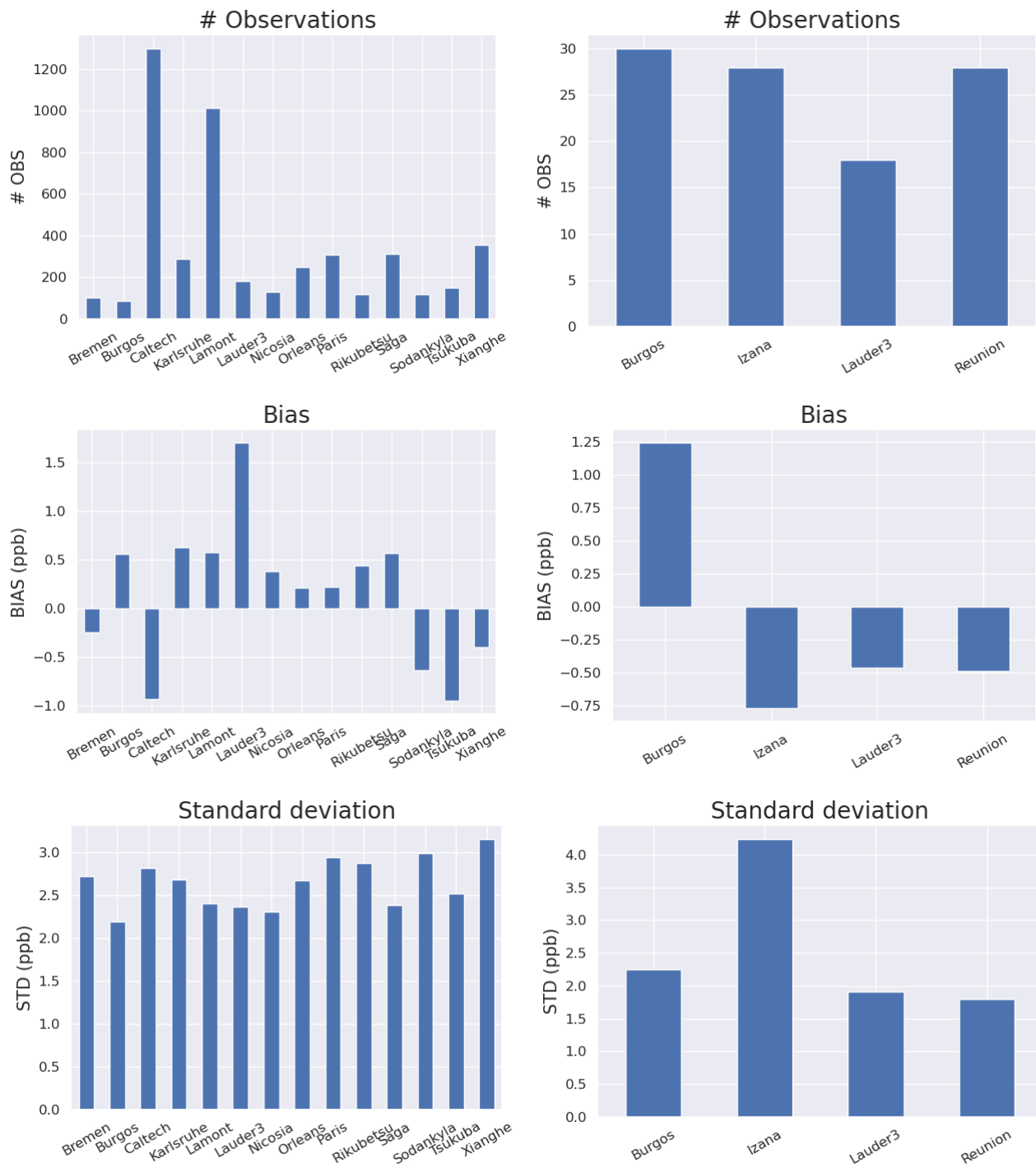
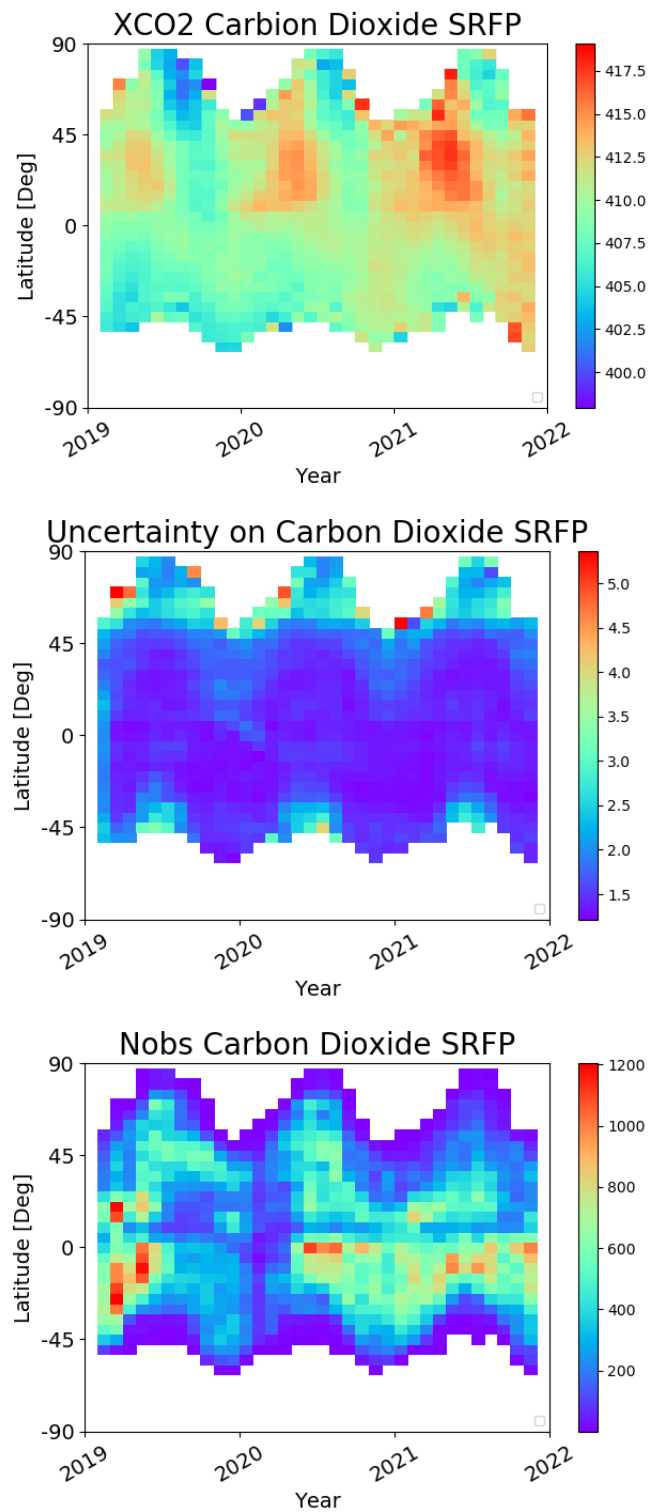




Figure 3: The CO2\_GO2\_SRFP global dataset in slices of 10 degrees latitude as a function of time. The yearly increase in XCO2 concentrations can clearly be seen.





### 2.1.2 Stability

Stability (both linear and year-to-year variability) is an essential part of the validation and can reveal potential degradation or other time-dependent effects in the GOSAT-2 data products.

Figure 4 and Figure 5 show the timeseries for the individual stations. As can be seen the time coverage for different stations can differ significantly and occasionally gaps occur due to maintenance of the TCCON station.

To determine the linear stability, we add all co-located TCCON measurements together and fit a linear relation to the remaining bias as a function of time. The year-to-year bias variability is the difference between the minimum of the bias in one year versus the maximum of the bias in one year. The results are shown in Table 1.



Figure 4: Timeseries for the individual stations for normal soundings for CO<sub>2</sub>\_GO2\_SRFP. The blue points represent the daily average of the TCCON data and the grey points are all the retrieved GOSAT-2 XCO<sub>2</sub> data.

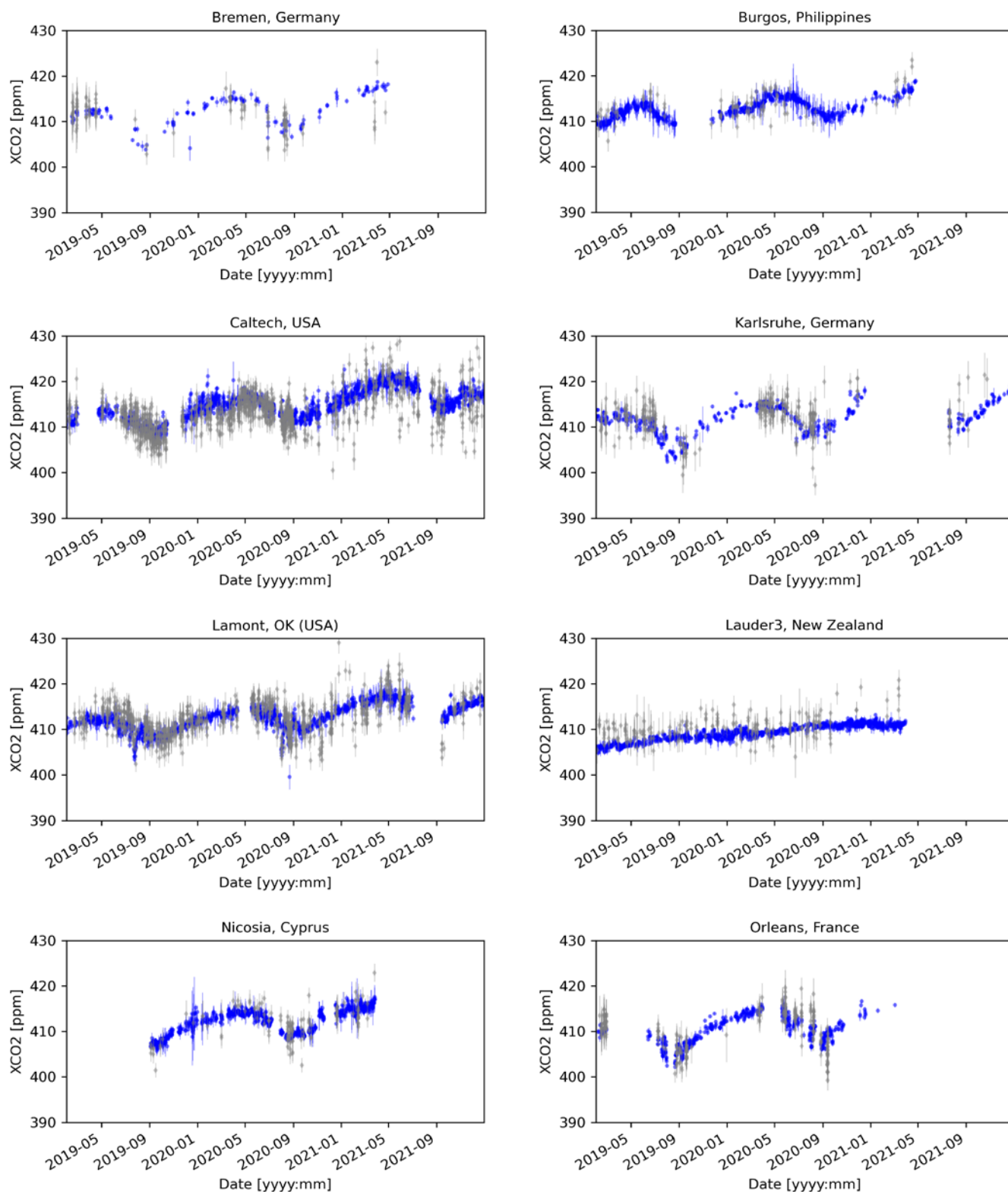




Figure 4 cont.

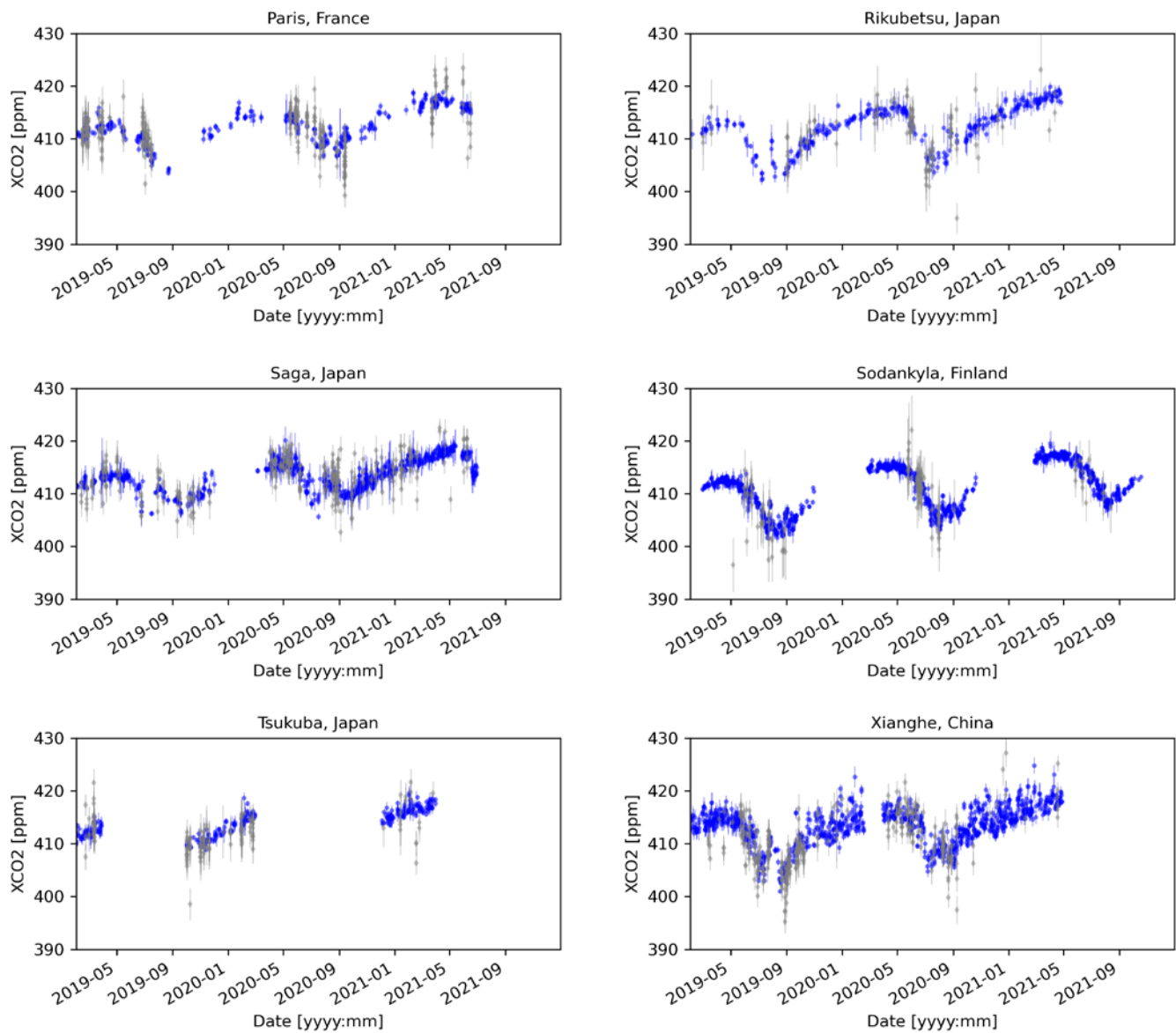
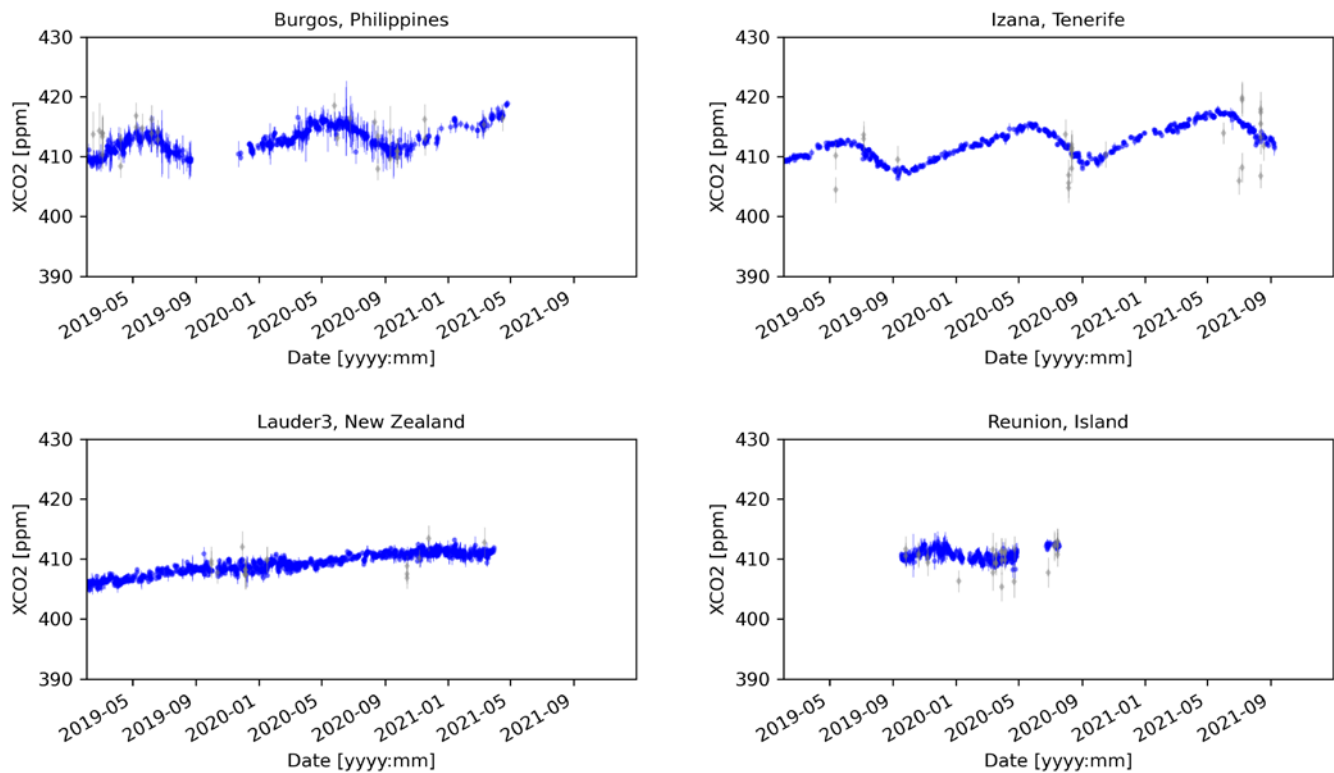




Figure 5: Timeseries for the individual stations for sunglint for CO<sub>2</sub>\_GO2\_SRFP. The blue points represent the daily average of the TCCON data and the grey points are all the retrieved GOSAT-2 XCO<sub>2</sub> data.





### 2.1.3 Validation summary

The validation results are summarised in the table below.

Table 1 - Product Quality Summary Table for product CO2\_GO2\_SRFP. T, B and G refer to threshold, breakthrough and goal, respectively.

Product Quality Summary Table for Product: CO2_GO2_SRFP Level: 2, Version: 2.0.0, Time period covered: 02.2019 – 12.2021				
Parameter [unit]	Achieved performance	Requirement	TR	Comments
Single measurement precision (1-sigma) in [ppm]	2.78	< 8 (T) < 3 (B) < 1 (G)	-	-
Uncertainty ratio: Ratio reported uncertainty to standard deviation of satellite-TCCON difference	0.80	-	-	No requirement but value close to unity expected for a high quality data product.
Mean bias [ppm]	-0.02	-	-	No requirement but value close to zero expected for a high quality data product.
Accuracy: Relative systematic error [ppm]	Spatial: 0.56 +/- 0.07 Spatiotemporal: 0.67 +/- 0.38	< 0.5	Probability that accuracy TR is met: 33 %	-
Stability: Drift [ppm/year]	0.01 +/- 0.08 (1-sigma)	< 0.5	Probability that stability TR is met: 99 %	-
Stability: Year-to-year bias variability [ppm/year]	0.35 +/- 0.15 (1-sigma)	< 0.5	-	-



### 2.1.4 GOSAT-GOSAT2 Intercomparison

In this section we report on the comparison of the GOSAT-2 SRFP XCO<sub>2</sub> data versus co-located GOSAT-1. Figure 6 shows a comparison of GOSAT-2 and GOSAT FP-CO<sub>2</sub> for both the non- (top) and bias-corrected (bottom) product. Table 2 shows a summary of the corresponding statistics. The bias-correction of observations has been performed with TCCON observations as described in the previous section. The products from the two satellites do not show high correlations. For sunglint mode, the bias-corrected comparison shows a better bias, correlation and standard deviation than the non-corrected version. However, this is not the case for land soundings where the bias and standard deviation are increased, and correlation reduced, with the bias correction. These results may be due to the different bias correction techniques applied in GOSAT and GOSAT-2 SRFP CO<sub>2</sub> products, where a bias correction based on the retrieved O<sub>2</sub> ratio (the ratio between retrieved and prior O<sub>2</sub> column) is used for GOSAT, whereas for GOSAT-2 the bias correction is based on the retrieved albedo at 1.6  $\mu$ m as this provided the best TCCON validation. This would explain how we achieve good results from the TCCON validation, but low correlations between GOSAT and GOSAT-2.

**Table 2.** Summary of the comparison of SRFP-CO<sub>2</sub> GOSAT vs GOSAT-2 for daily 1°x1° mean concentrations. Period covered is Feb 2019 to Dec 2021. The bias, standard deviation (precision), Pearson's correlation coefficient and number of observations (N) are given, for both the bias corrected and non-bias corrected values in land and glint mode.

	Land		Glint	
Parameter	Bias-Corrected	Non-corrected	Bias-Corrected	Non-Corrected
N	2296	2296	2926	2926
Correlation	0.28	0.31	0.22	0.15
Bias [ppm]	-2.21	-0.78	-0.32	3.38
Single measurement precision in ppm (std)	3.44	3.64	2.65	3.05





**Figure 6:** Comparison of normal and glint single soundings of SRFP-CO<sub>2</sub> with co-located GOSAT and GOSAT-2 measurements for the period 2019-2021, for bias corrected and non-bias corrected data. Bias and standard deviation values are given in ppm.

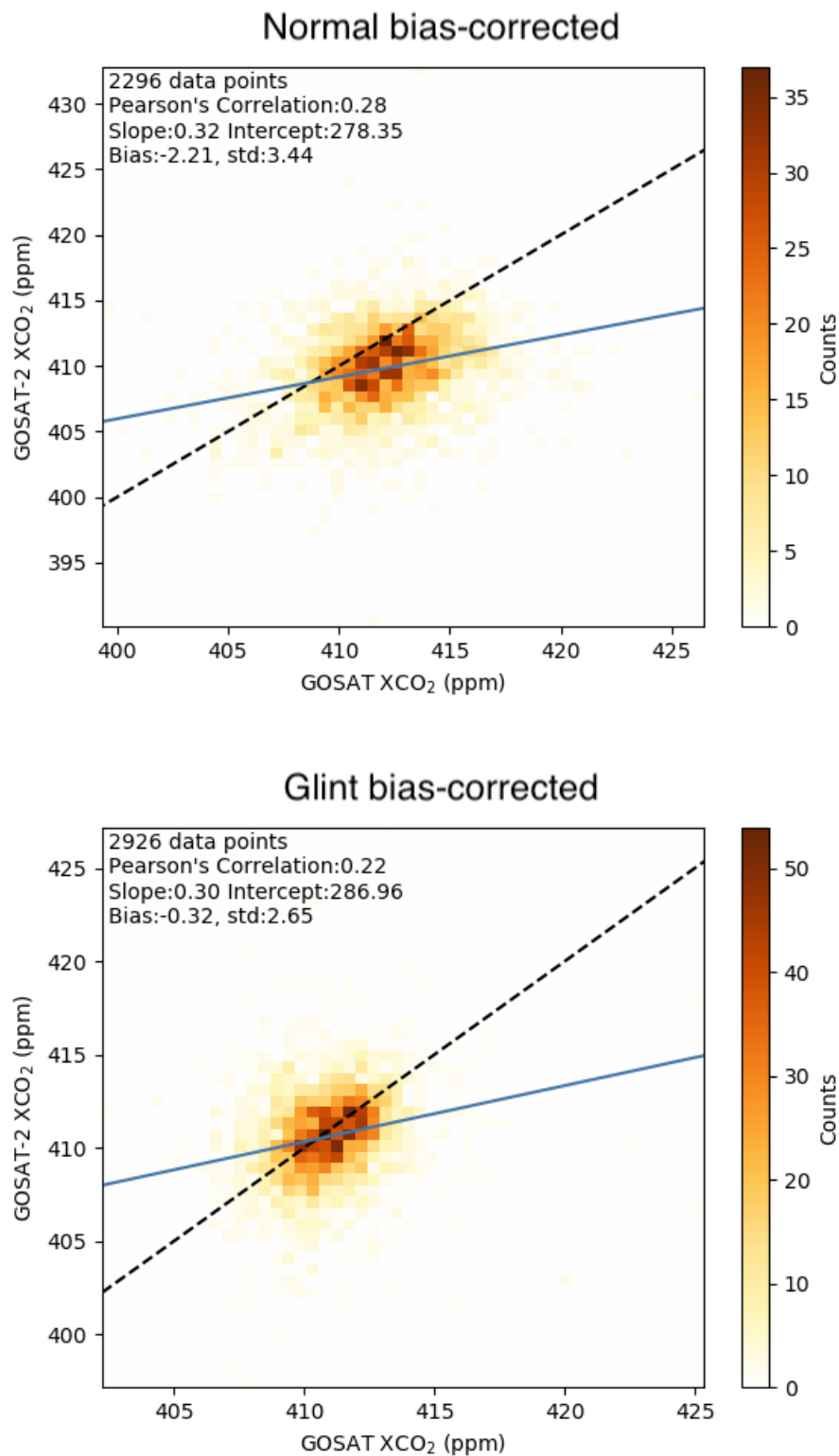
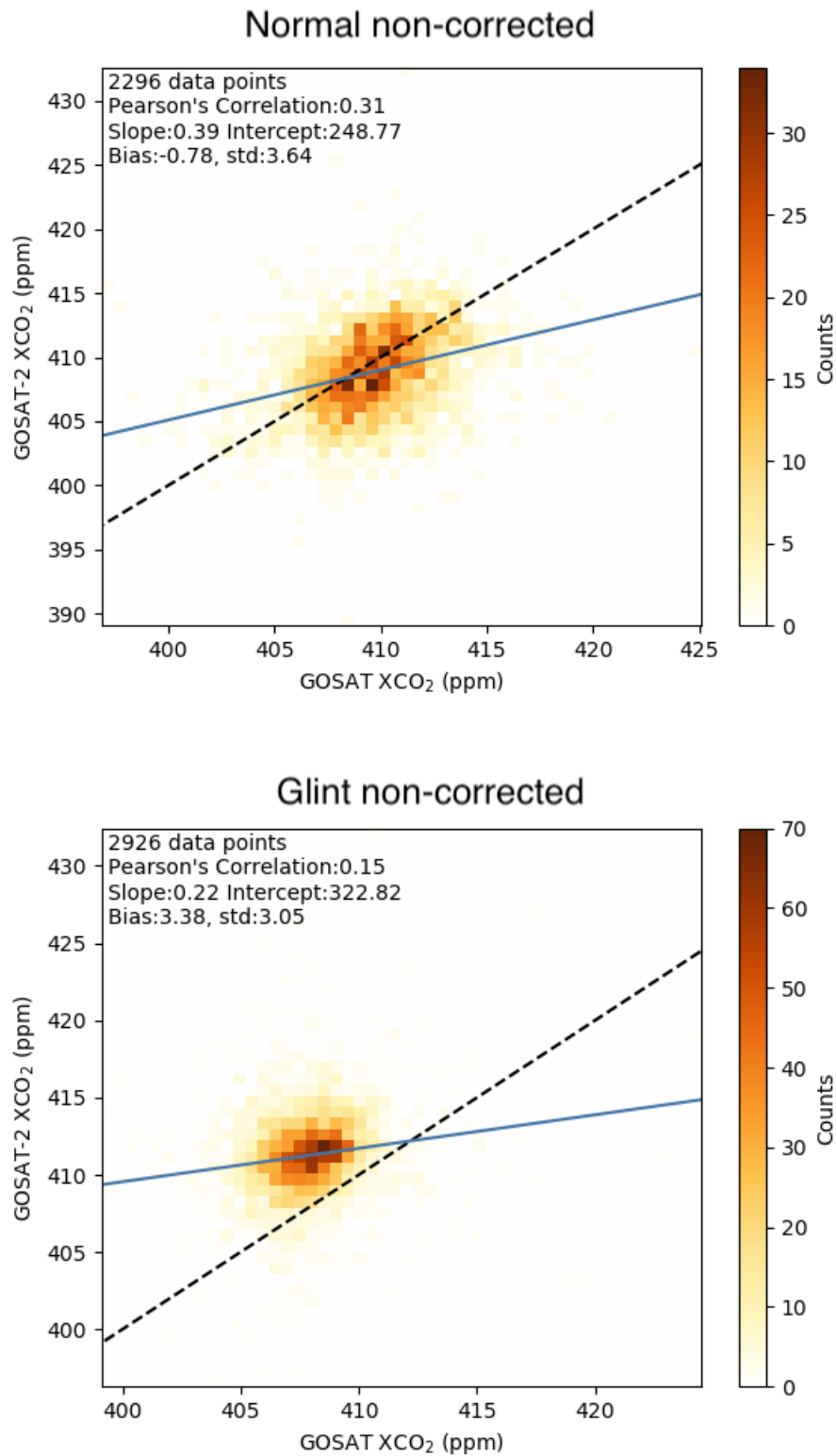




Fig 6. continued





## 2.2 Product CH<sub>4</sub>\_GO<sub>2</sub>\_SRFP

### 2.2.1 Validation

Figure 7 shows a very strong correlation of the retrieved (bias-corrected) XCH<sub>4</sub> with the TCCON XCH<sub>4</sub> ( $R > 0.8$ ). This gives us confidence that our bias correction based on the retrieved albedo works correctly and takes out most of the bias.

In the case of normal observations, the station-to-station standard deviation is 1.86 ppb. As is the case for CO<sub>2</sub>, Caltech and Lamont show the largest number of observations. Lauder has a large remaining bias of  $\sim 7$  ppb, comparable also to that of Rikubetsu. Figure 8 shows in detail for each station the remaining bias and standard deviation for the co-located GOSAT-2 soundings for the period between the years 2019 to 2021. For sunglint we removed Saga from the comparison as using the static spatial co-location criterion it only had limited co-located measurements.

Figure 9 presents Hovmöller diagrams of XCH<sub>4</sub> as well as the uncertainty on this parameter, along with the number of observations across the range of GOSAT-2 observations.



Figure 7: Validation of XCH<sub>4</sub> retrieved by GOSAT-2-RemoTeC with ground based TCCON measurements for normal (top) and sunglint (bottom) soundings. N indicates the number of GOSAT-2-TCCON collocations, Bias is the average difference (for individual measurements) between GOSAT-2 and TCCON, Std the standard deviation of the GOSAT-2 TCCON difference (for individual measurements) and the Pearson's correlation coefficient between the two set of observations is also given.

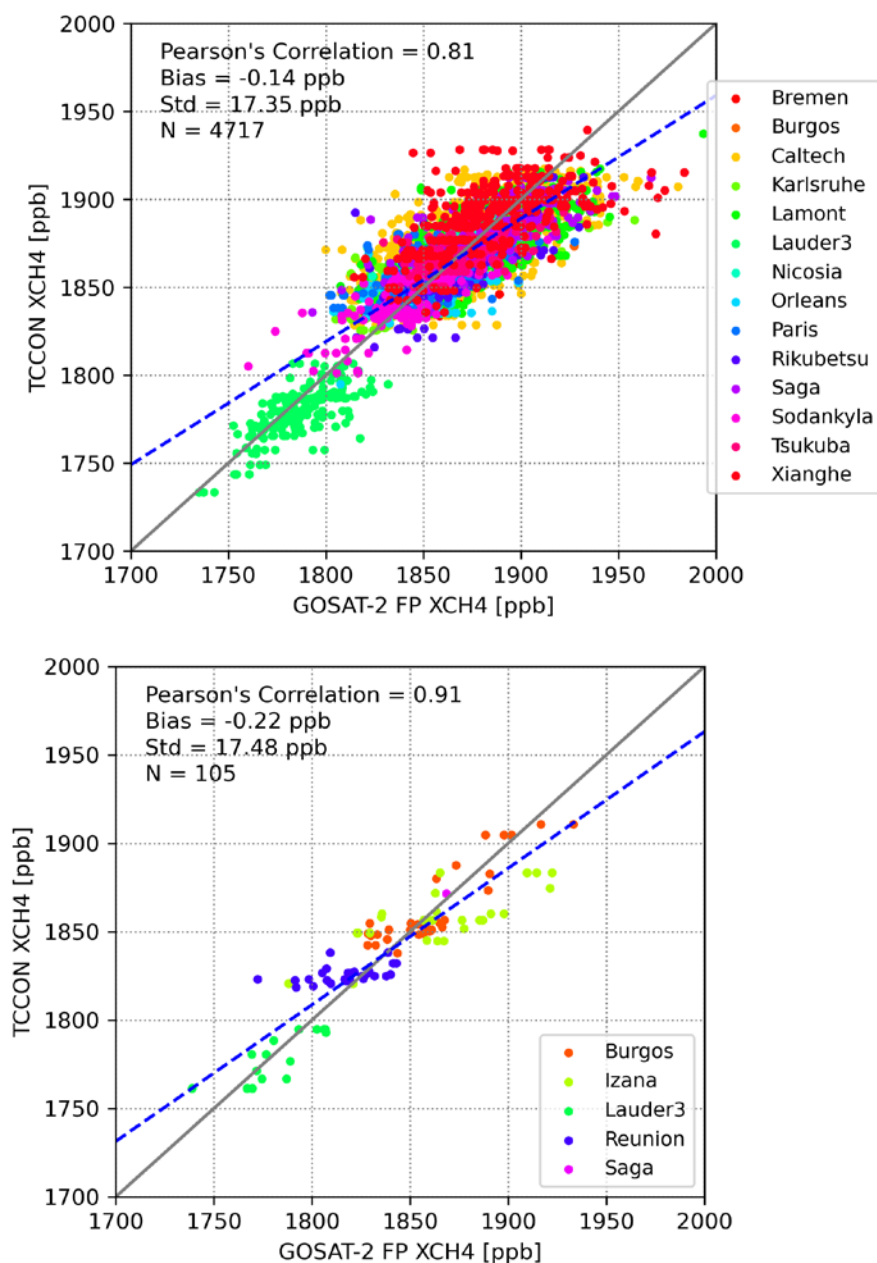




Figure 8: The bias, standard deviation and # of measurements per station for normal (left) and sunglint (right) soundings for the period between the year 2019 and 2021.

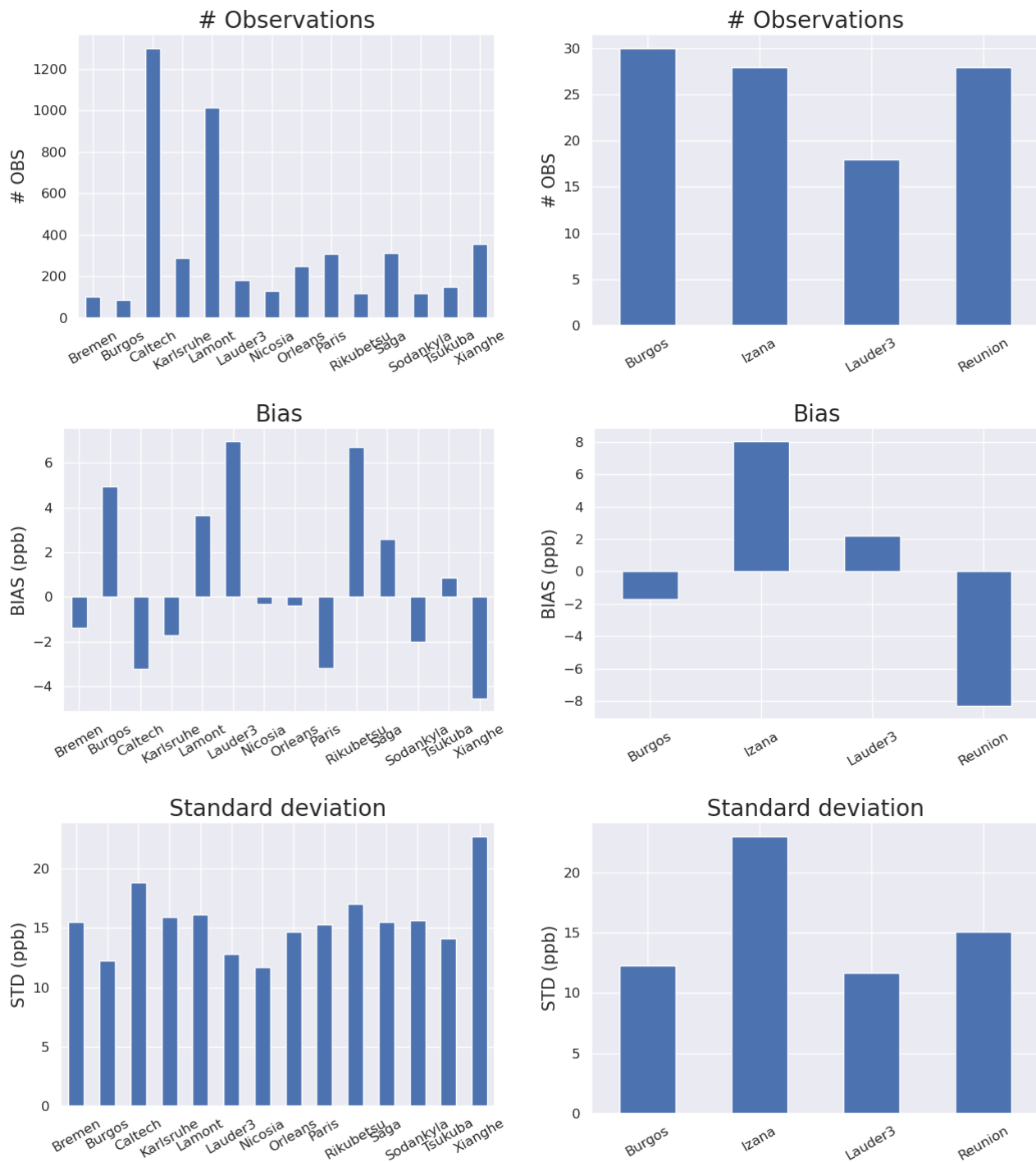
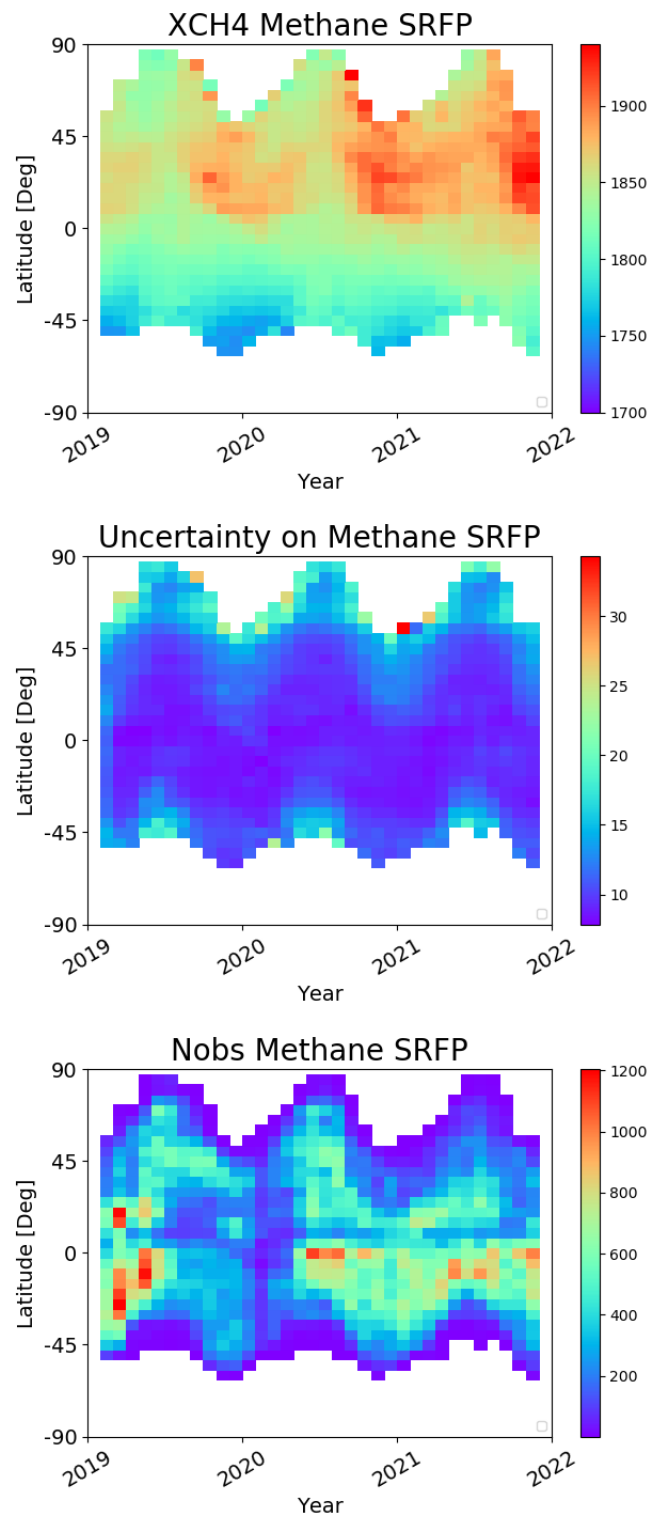




Figure 9: The CH<sub>4</sub>\_GO2\_SRFP global dataset in slices of 10 degrees latitude as a function of time. The increase in XCH<sub>4</sub> concentrations during the last couple of years can clearly be seen.





### 2.2.2 Stability

Stability (both linear and year-to-year variability) is an essential part of the validation and can reveal potential degradation or other time-dependent effects in the GOSAT-2 data products.

Figures 10 and 11 show the timeseries for the individual stations. As can be seen the time coverage for different stations can differ significantly and occasionally gaps occur due to maintenance of the TCCON station.

To determine the linear stability, we add all co-located TCCON measurements together and fit a linear relation to the remaining bias as a function of time. The year-to-year bias variability is the difference between the minimum of the bias in one year versus the maximum of the bias in one year. The results are shown in Table 3.



Figure 10: Timeseries for the individual stations for normal soundings for CH<sub>4</sub>\_GO2\_SRFP. The blue points represent the daily average of the TCCON data and the grey points are all the retrieved GOSAT-2 XCH<sub>4</sub> data.

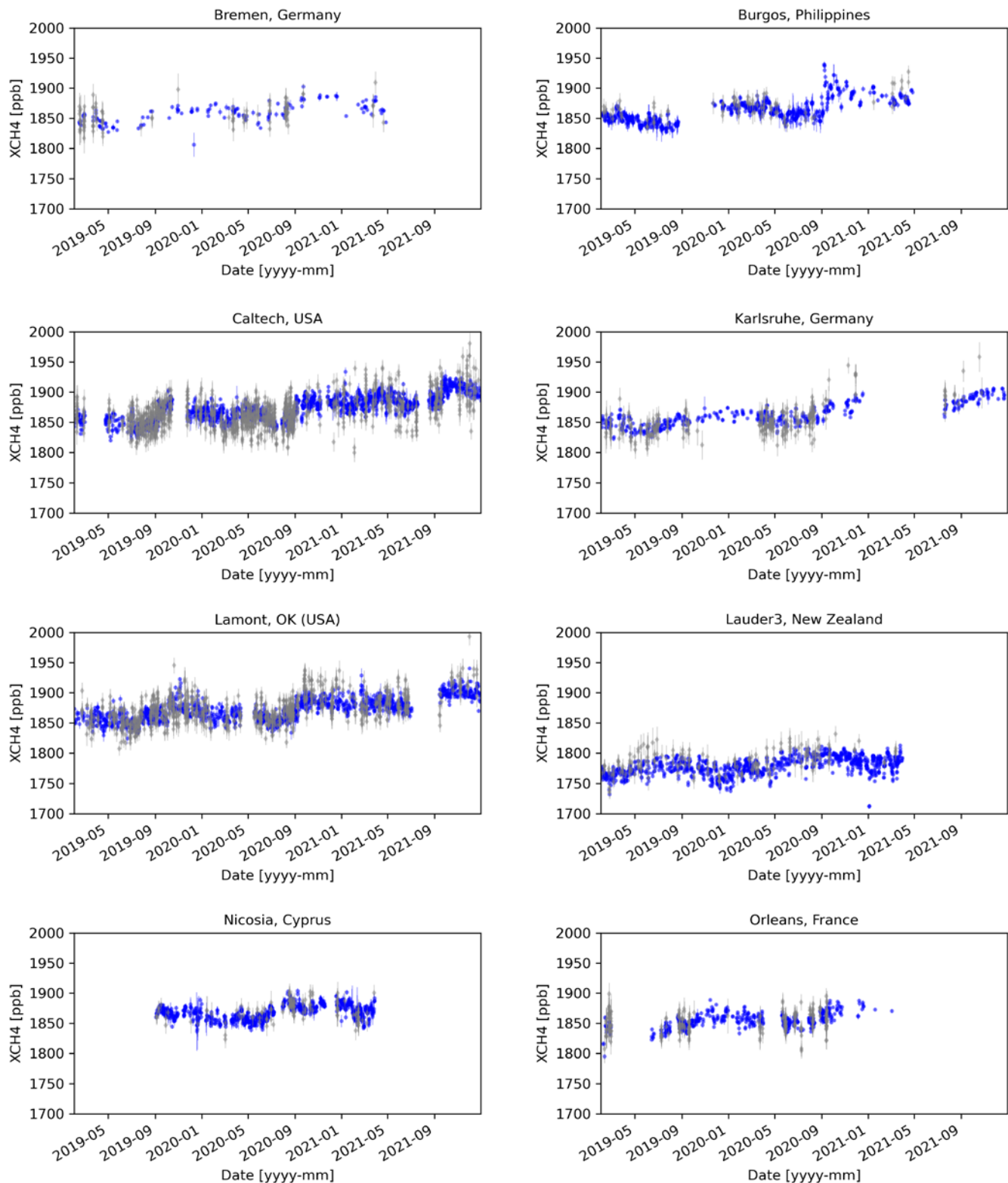






Figure 10 cont.

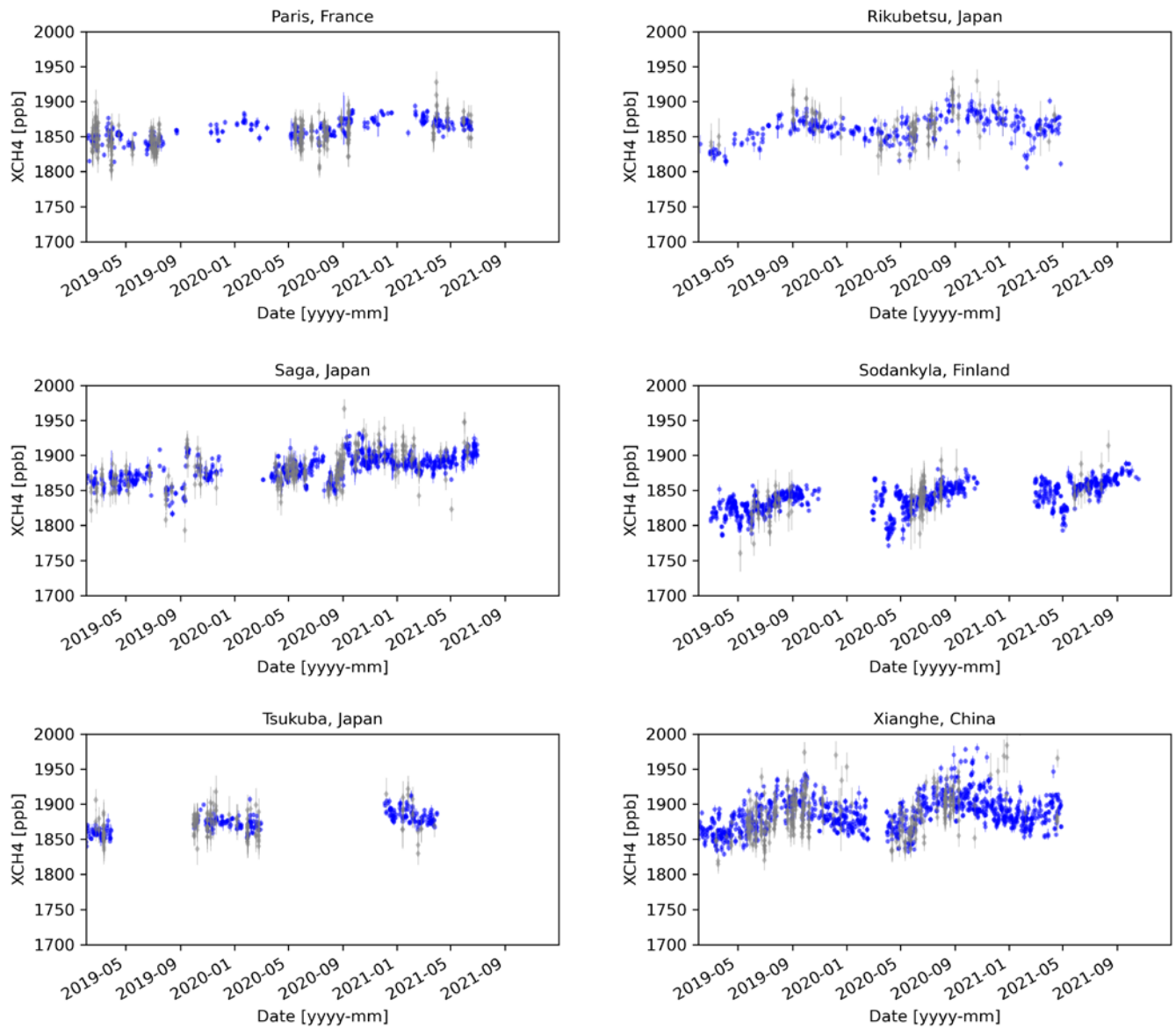
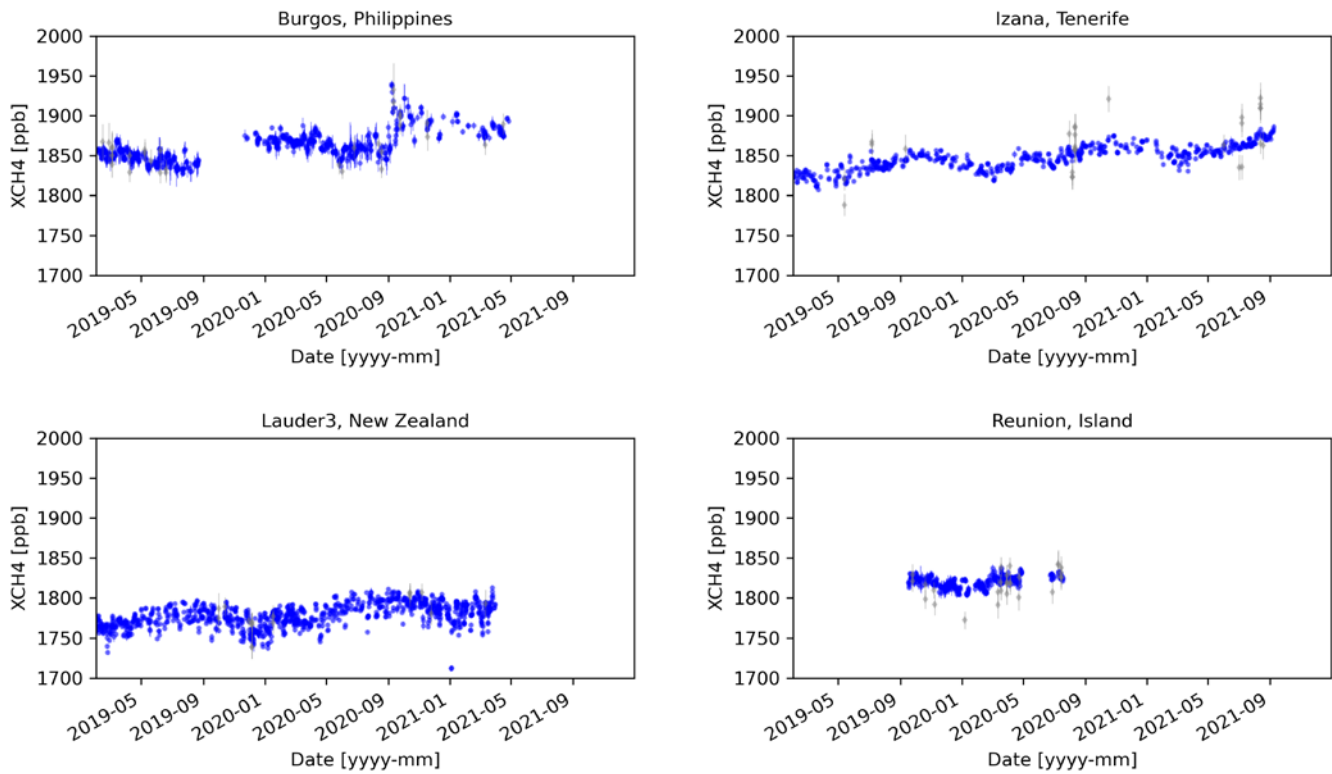




Figure 11: Timeseries for the individual stations for sunglint for CH<sub>4</sub>\_GO<sub>2</sub>\_SRFP. The blue points represent the daily average of the TCCON data and the grey points are all the retrieved GOSAT-2 XCH<sub>4</sub> data.





### 2.2.3 Validation summary

The validation results are summarised in Table 3.

Table 3 - Product Quality Summary Table for product CH4\_GO2\_SRFP. T, B and G refer to threshold, breakthrough and goal, respectively.

Product Quality Summary Table for Product: CH4_GO2_SRFP Level: 2, Version: 2.0.0, Time period covered: 02.2019 – 12.2021				
Parameter [unit]	Achieved performance	Requirement	TR	Comments
Single measurement precision (1-sigma) in [ppb]	17.35	< 34 (T) < 17 (B) < 9 (G)	-	-
Uncertainty ratio: Ratio reported uncertainty to standard deviation of satellite-TCCON difference	0.79	-	-	No requirement but value close to unity expected for a high quality data product.
Mean bias [ppb]	-0.14	-	-	No requirement but value close to zero expected for a high quality data product.
Accuracy: Relative systematic error [ppb]	Spatial: 1.86 +/- 0.4 Spatiotemporal: 4.36 +/- 1.69	< 10	Probability that accuracy TR is met: 99 %	-
Stability: Linear bias trend [ppb/year]	1.73 +/- 1.33 (1-sigma)	< 3	Probability that stability TR is met: 83%	-
Stability: Year-to-year bias variability [ppb/year]	9.90 +/- 4.10 (1-sigma)	< 3	-	-



#### 2.2.4 GOSAT-GOSAT2 Intercomparison

In this section we report on the comparison of the GOSAT-2 SRFP XCH<sub>4</sub> data versus co-located GOSAT-1. Figure 12 shows a comparison of GOSAT-2 and GOSAT FP-CH<sub>4</sub> for both the non- (top) and bias-corrected (bottom) product. Table 4 shows a summary of the corresponding statistics. The bias-correction of observations has been performed with TCCON observations as described in the previous section. Overall, the products from the two satellites compare fairly well with relatively small biases, high correlations. The bias-corrected comparison shows a better bias and standard deviation than the non-corrected version. This gives us confidence that the bias correction performs well. In the bias corrected comparison, land soundings show a higher residual bias between GOSAT and GOSAT-2 compared to sunglint soundings and the standard deviation is also higher. This is contrary to what is found for the PR-CH<sub>4</sub> product. It is possible that this is due to the slightly larger number of data points in sunglint mode compared to land observations (~30 %).



**Figure 12:** Comparison of normal and glint single soundings of SRFP-CH<sub>4</sub> with co-located GOSAT and GOSAT-2 measurements for the period 2019-2021, for bias corrected and non-bias corrected data. Bias and standard deviation values are given in ppb.

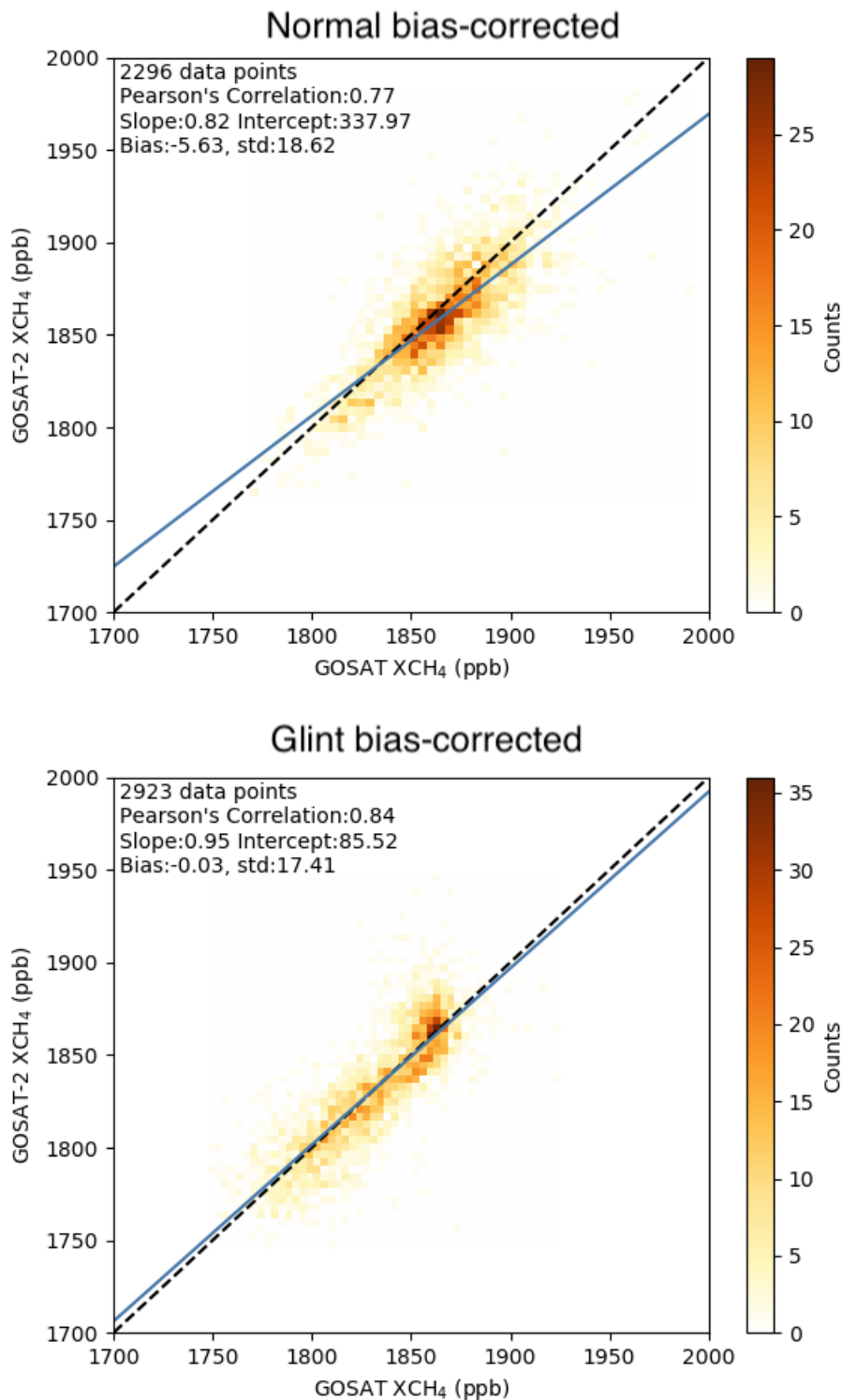
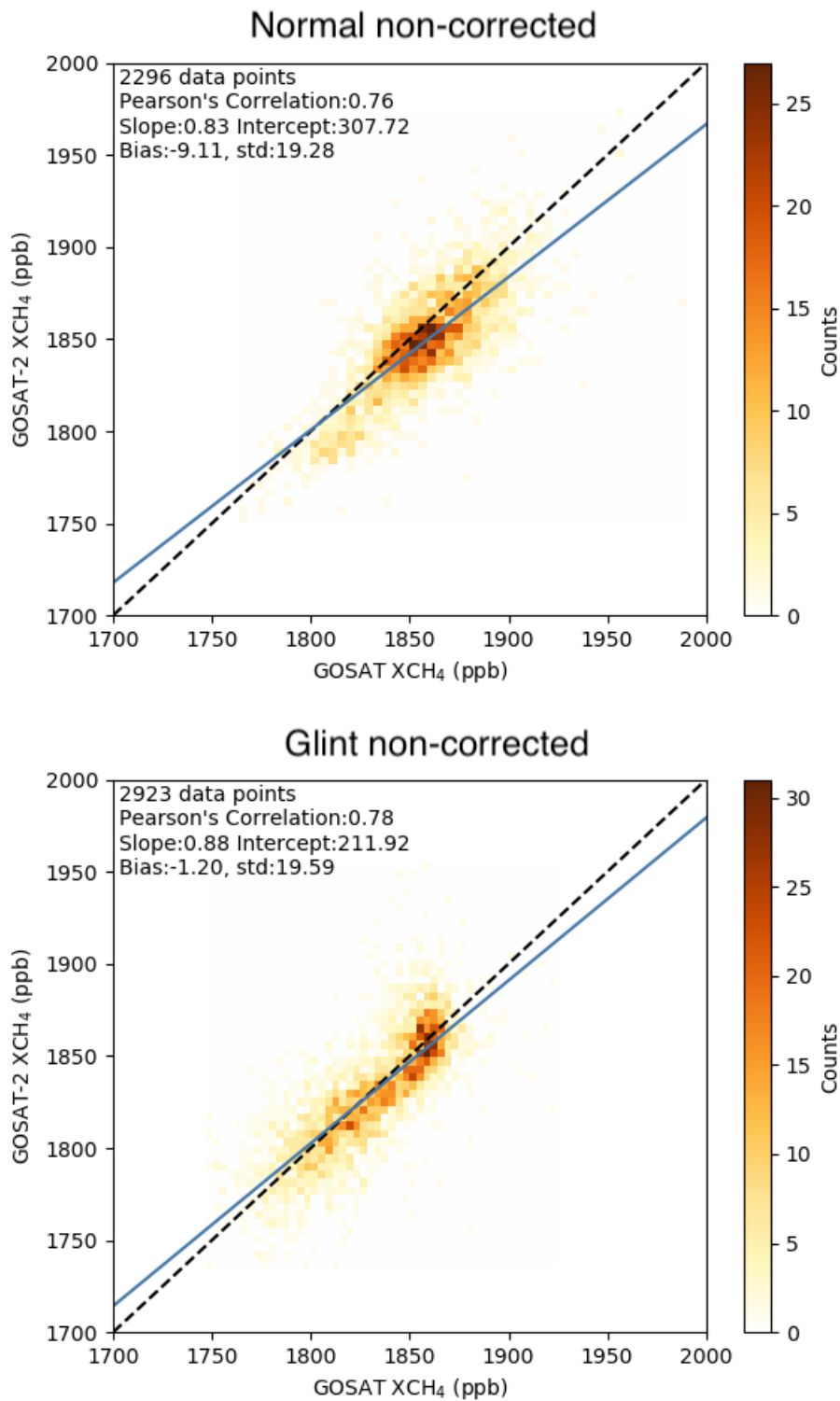




Fig 12. continued





**Table 4.** Summary of the comparison of SRFP-CH<sub>4</sub> GOSAT vs GOSAT-2 for daily 1°x1° mean concentrations. Period covered is Feb 2019 to Dec 2021. The bias, standard deviation (precision), Pearson's correlation coefficient and number of observations (N) are given, for both the bias corrected and non-bias corrected values in land and glint mode.

	Land		Glint	
Parameter	Bias-Corrected	Non-corrected	Bias-Corrected	Non-Corrected
N	2296	2296	2923	2923
Correlation	0.82	0.83	0.84	0.78
Bias [ppm]	-5.63	-9.11	-0.03	1.20
Single measurement precision in ppm (std)	18.62	19.28	17.41	19.59

### 3. Application(s) specific assessments

No application specific assessments have been carried out.

### 4. Compliance with user requirements

For the CH<sub>4</sub>\_GO<sub>2</sub>\_SRFP product we reached a 99 % chance that the TR is met for accuracy and an 83 % chance the TR is met for stability. For CO<sub>2</sub>\_GO<sub>2</sub>\_SRFP we only reached a 33 % chance that the TR is met for accuracy but a 99 % chance that the TR is met for stability.



## References

**CMUG-RBD, 2010:** Climate Modelling User Group Requirements Baseline Document, Deliverable 1.2, Number D1.2, Version 1.3, 2 Nov 2010.

**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, link: [http://www.esa-ghg-cci.org/?q=webfm\\_send/344](http://www.esa-ghg-cci.org/?q=webfm_send/344), 2016.

**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/utils/common/documents/jcgm/JCGM\\_100\\_2008\\_E.pdf](http://www.bipm.org/utils/common/documents/jcgm/JCGM_100_2008_E.pdf), 2008.

**Laughner et al. 2021:** Laughner, J., Andrews, A., Roche, S., Kiel, M., and Toon, G.: ginput v1.0.10: GGG2020 prior profile software (Version 1.0.10), <https://doi.org/10.22002/D1.1944>, 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 (CO<sub>2</sub> and CH<sub>4</sub>) 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 (CO<sub>2</sub> and CH<sub>4</sub>) data products (project C3S\_312b\_Lot2), Version 2.11, 9-April-2020, pp. 80, 2020.

**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, Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences, 369, 2087–2112.

**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](https://doi.org/10.14291/tccon.ggg2014.documentation.R0/1221662)), 2015.



