ECMWF COPERNICUS REPORT

Copernicus Climate Change Service

# Product Quality Assessment Report (PQAR) – ANNEX B for products CO2_GO2_SRFP, CH4_GO2_SRFP (v2.0.0, 2019-2022)

## C3S2_312a_Lot2_DLR – Atmosphere

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## 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 | 04-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:<br>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 2nd review. Several improvements at various places. | All |
| 6.3 | 02-March-2023 | Minor update after 2nd review to generate clean version. | All |
| 7.0 | 24-August-2023 | Update for CDR7:<br>GOSAT-2 retrievals (2019 – 2022) | All |
| 7.1 | 30-October-2023 | Update after review | All |
| 7.2 | 17-November-2023 | Minor update 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_GO2_SRFP | CDR 7 | 2.0.0 | 31-Aug-2023 |
| WP2-FDDP-GHG-v2 | CH4_GO2_SRFP | CDR 7 | 2.0.0 | 31-Aug-2023 |

# Related documents

| Reference ID | Document |
| --- | --- |
| D1 | **Main PQAR:**<br><br>Buchwitz, M., et al., Product Quality Assessment Report (PQAR) – Main document for Greenhouse Gas (GHG: $CO_2$ & $CH_4$) data set CDR 7 (2003-2027), project C3S2_312a_Lot2_DLR – Atmosphere, 2023.<br><br>***Important Note:***<br><br>*This document is an ANNEX to the Main PQAR document and contains the quality assessment results of the data provider.*<br><br>***For the final overall quality assessment results of the data products described in this document see the Main PQAR document.*** |
| D2 | **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 ($CO_2$ and $CH_4$) data products, Version 3.1, 19-February-2021, pp. 81, 2021.<br><br>Latest version:<br>http://wdc.dlr.de/C3S_312b_Lot2/Documentation/GHG/C3S2_312a_Lot2_TRD-GAD_GHG_latest.pdf |

# 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., $XCO_2$) 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*).

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

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

**<u>Breakthrough requirement</u>:** 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*).

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

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

**<u>Observing Cycle</u>** 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

# 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 ($CO_2$) and methane ($CH_4$) 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 $CO_2$ and $CH_4$, denoted $XCO_2$ (in parts per million, ppm) and $XCH_4$ (in parts per billion, ppb), respectively.
- Mid/upper tropospheric mixing ratios of $CO_2$ (in ppm) and $CH_4$ (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 $XCO_2$ and $XCH_4$ 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 CO2_GO2_SRFP and CH4_GO2_SRFP retrievals. In general, we find very good agreement with TCCON data for both modes (land and ocean) and for both products. Both have a very high degree of correlation with TCCON (R~0.75).

For the CO2_GO2_SRFP product the station-to-station bias is 0.34 ppm and a standard deviation of around 3.02 ppm is observed for most TCCON stations.

For the CH4_GO2_SRFP product the station-to-station bias is 3.00 ppb and a standard deviation of around 18.85 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 4 years and found that there has been no significant change in the bias over time, indicating very good detector stability.

We achieved both Target Requirements (TR) for accuracy and stability for the CH4_GO2_SRFP product, with 99 % and 99 % of meeting the requirement, respectively, while for CO2_GO2_SRFP we achieved a 99 % probabiliy that the TR is met for stability but only a 66 % chance that the TR is met for accuracy.

# Product validation methodology

Validation of the CH4_GO2_SRFP V2.0.0 and CO2_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 $XCH_4$ and $XCO_2$ 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 ±5 degree latitude and ±8 degree longitude of TCCON station
- GOSAT-2 sounding within ±2 hours of TCCON measurements

We then average all the TCCON measurements within ±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.

# Validation Results

## 1.2 Product CO2_GO2_SRFP

### 1.2.1 Validation

Figure 1 illustrates that the land soundings show a strong correlation of the retrieved (bias-corrected) $XCO_2$ with the TCCON $XCO_2$ (R = 0.77). The ocean soundings show a similarly high correlation (R = 0.75) despite the limited range of $XCO_2$ 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 2022. In the case of land observations, the station-to-station standard deviation is 0.34 ppm. Caltech/Edwards and Lamont have the largest number of co-locations and dominate the total statistical comparison. Stations Caltech and Edwards are spatially located in the same area. The largest bias is at Ny Alesund in Norway which shows a very large bias of over 6 ppm in magnitude. This is likely due to the very low number of observations at this high latitude station apparent in the upper left panel of Figure 2. Excluding Ny Alesund, the station with the highest bias is Lauder, Oklahoma (US) 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 $XCO_2$ 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 $XCO_2$ retrieved by GOSAT-2-RemoTeC with ground based TCCON measurements for land (top) and ocean/glint (bottom) soundings over the course of the full dataset (2019-2022). N indicates the number of GOSAT-2-TCCON colocations, $\mu$ is the average difference (for individual measurements) between GOSAT-2 and TCCON, $\sigma$ the standard deviation of the GOSAT-2 TCCON difference (for individual measurements) and R the Pearson's correlation coefficient between the two set of observations.

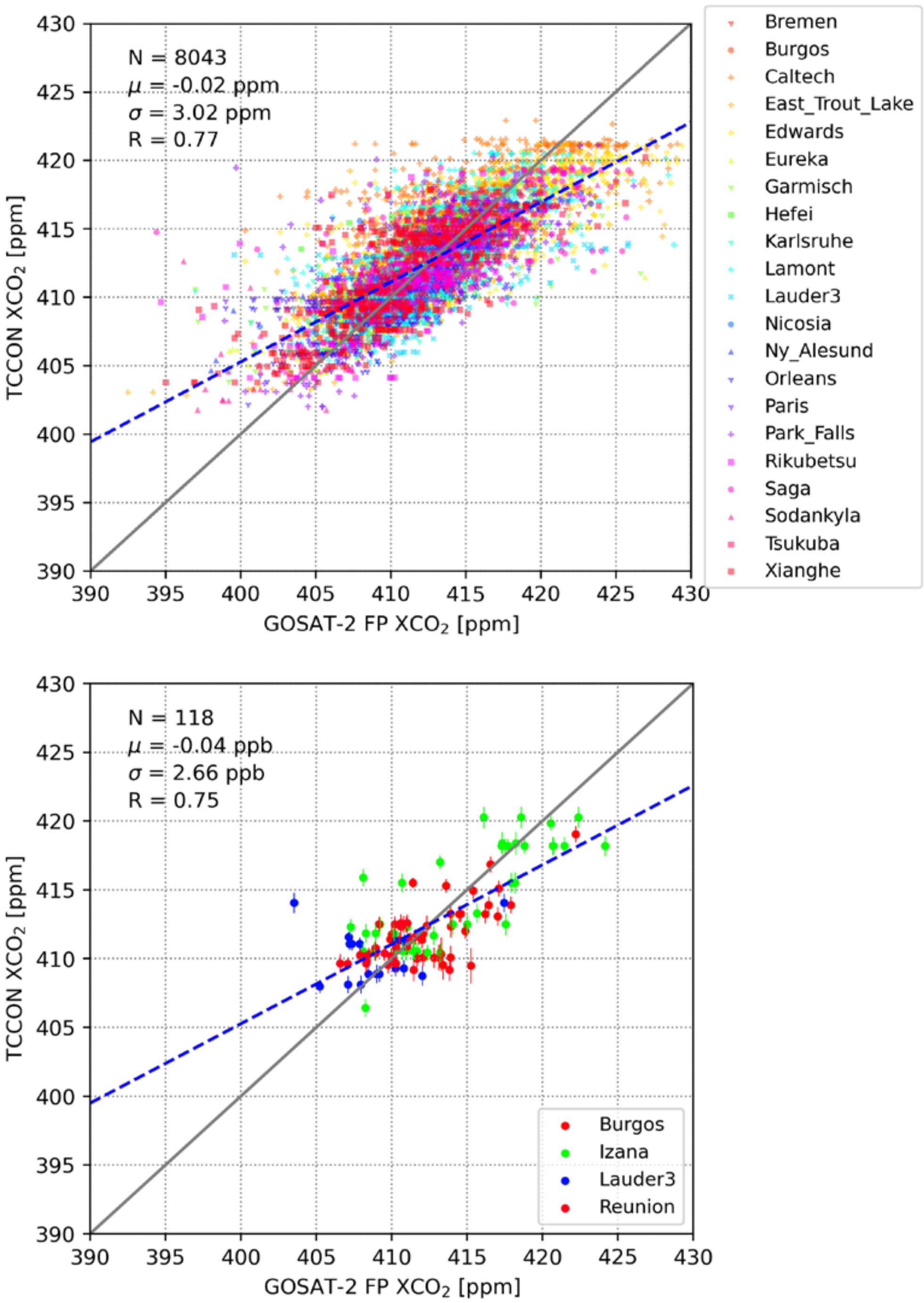


Figure 2: The bias, standard deviation and number of measurements per TCCON station for land (left) and ocean (right) soundings for the period between the year 2019 and 2022.

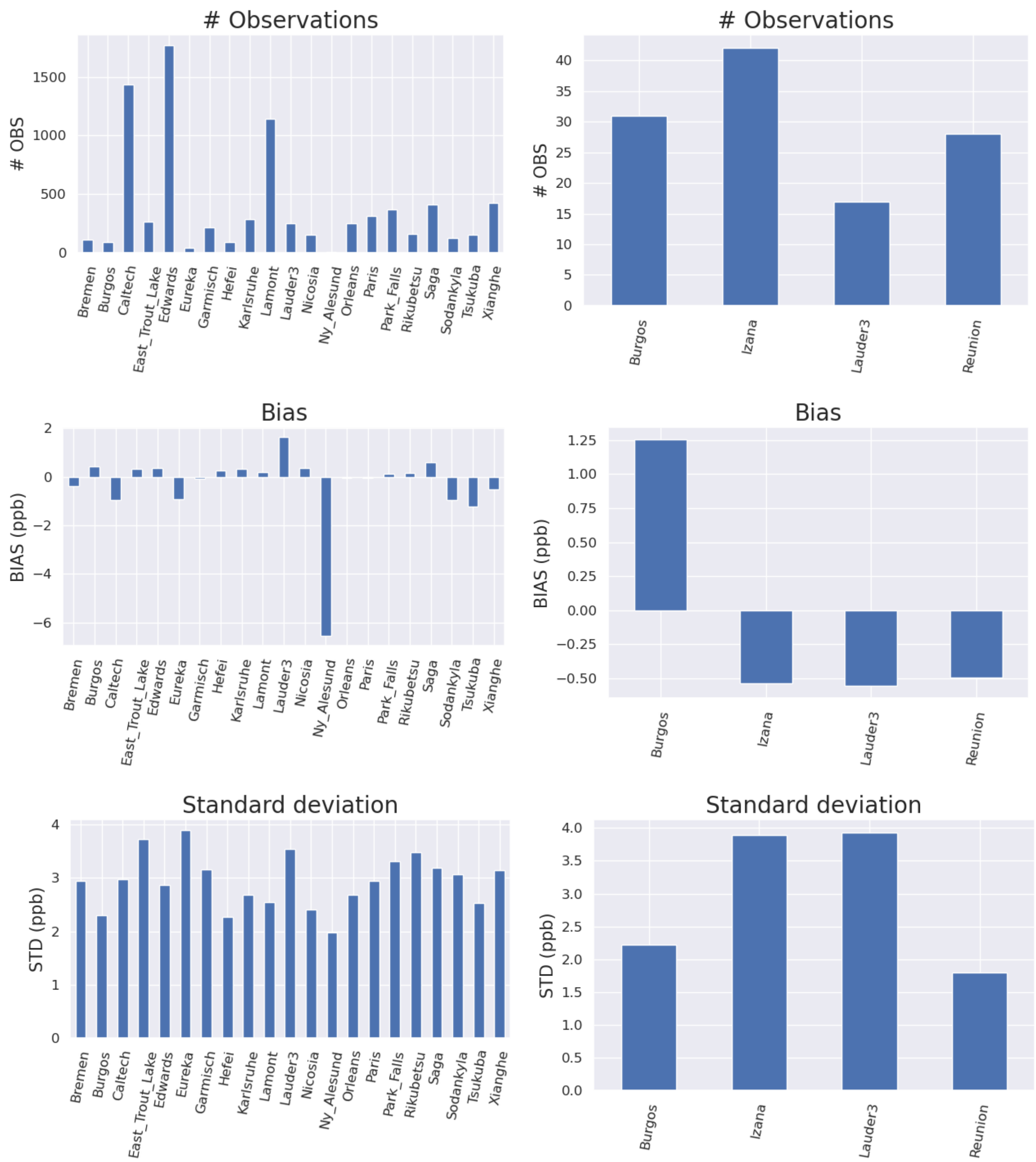
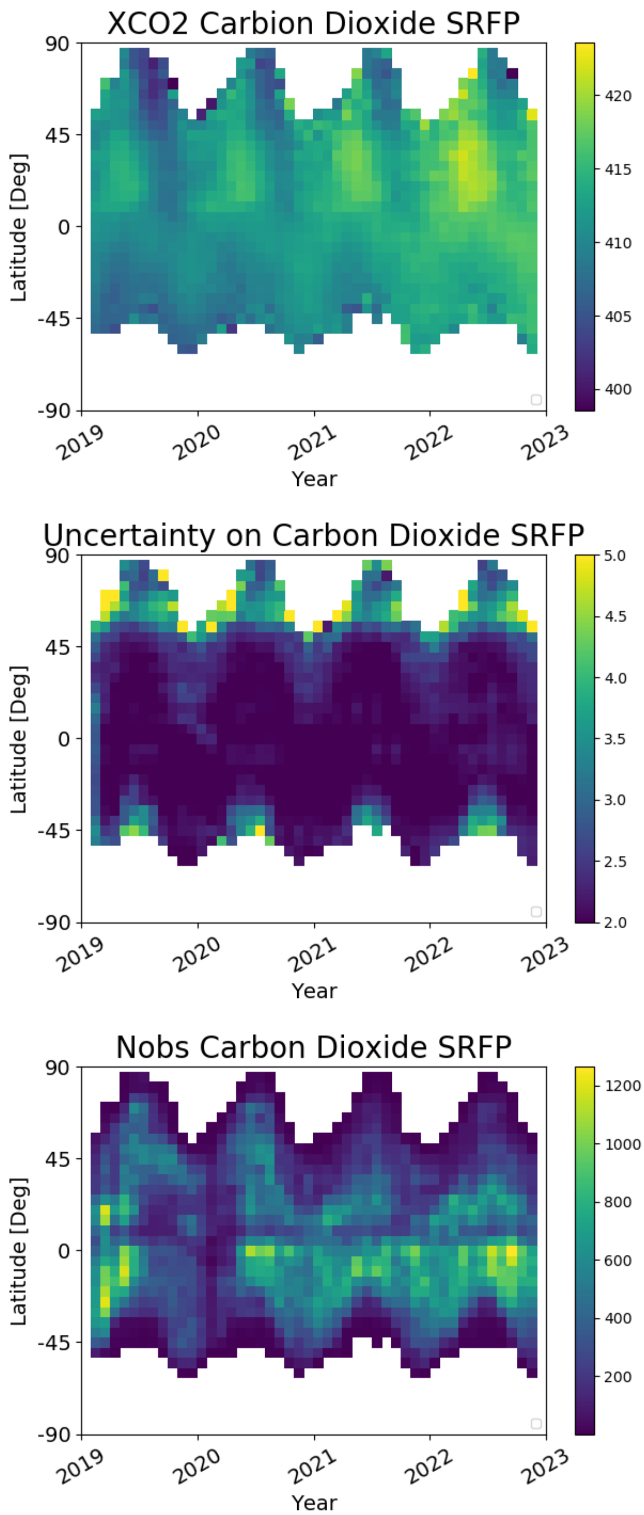


Figure 3: The CO2_GO2_SRFP global dataset in slices of 10 degrees latitude as a function of time. The yearly increase in $XCO_2$ concentrations can clearly be seen.



### 1.2.2 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.
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: *Upper panels:* Timeseries for the individual stations for land soundings for CO2_GO2_SRFP. The pink triangles represent the daily average $XCO_2$ of the TCCON data and the blue circles are all the retrieved GOSAT-2 data. *Lower panels:* Histogram of number of GOSAT-2 retrievals in bins over the time range in question.

Figure 4 cont.

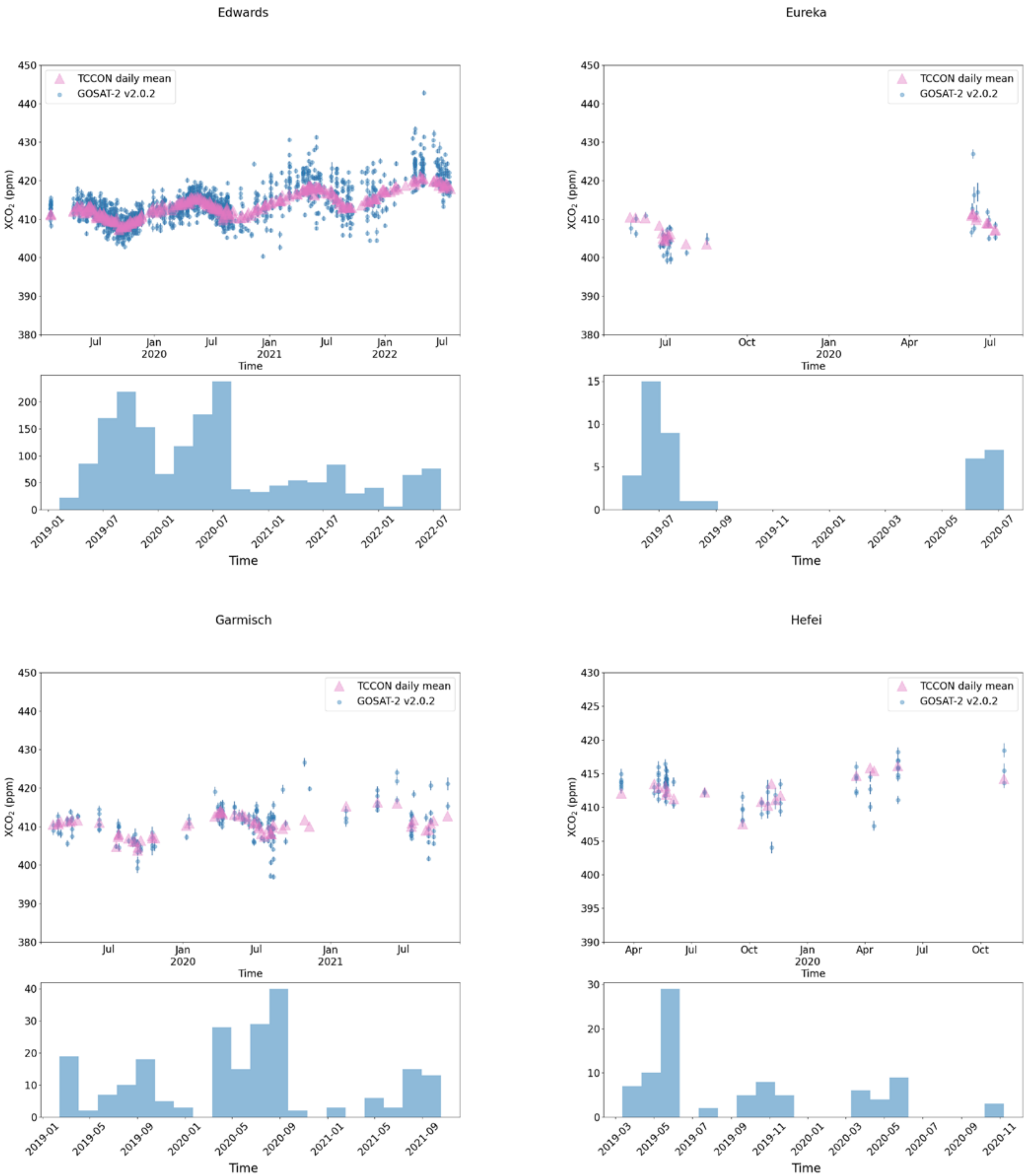
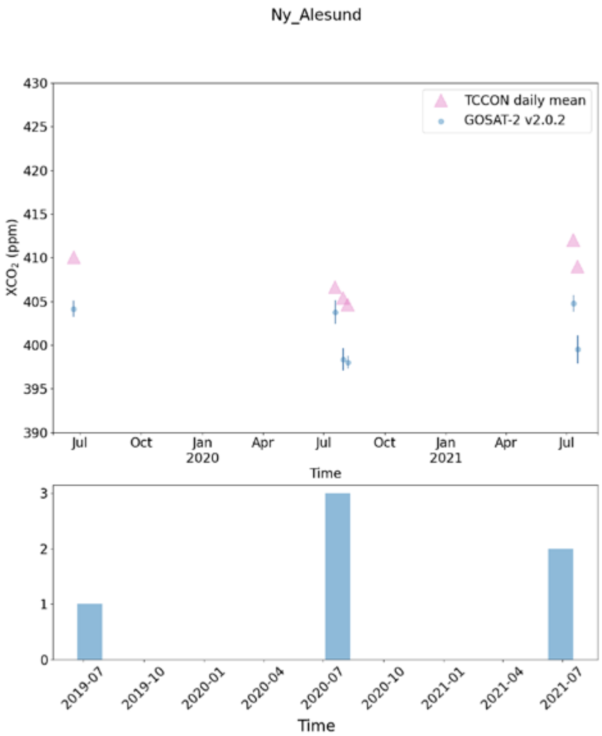
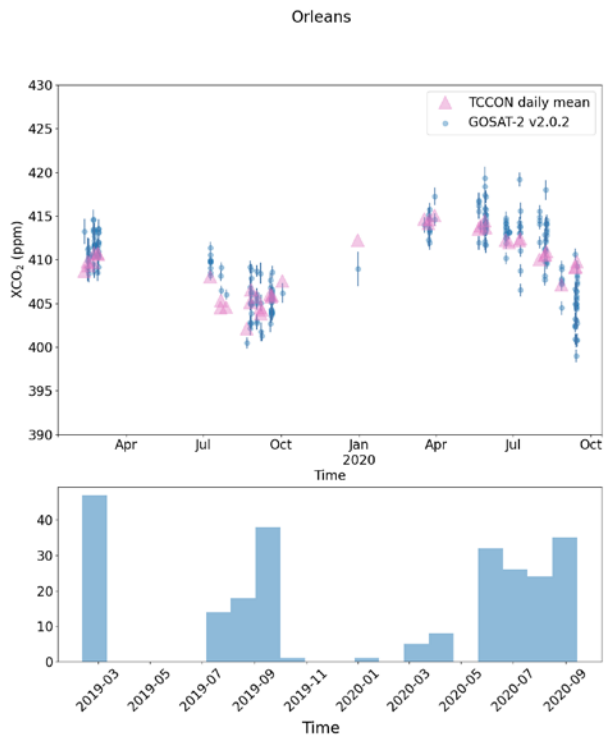
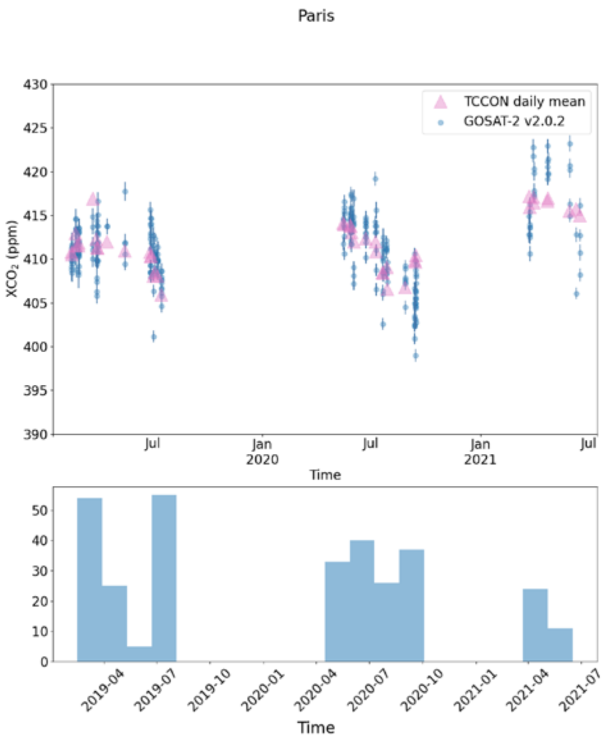


Figure 4 cont.

Figure 4 cont.



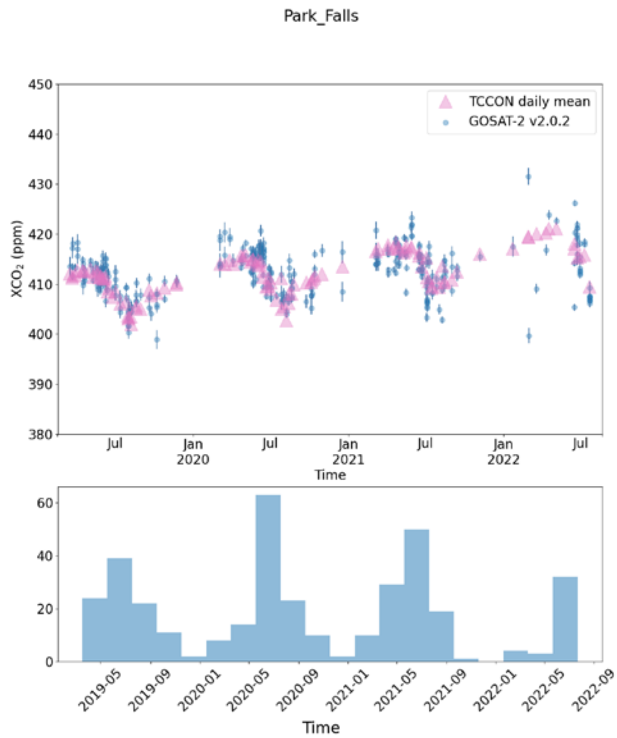
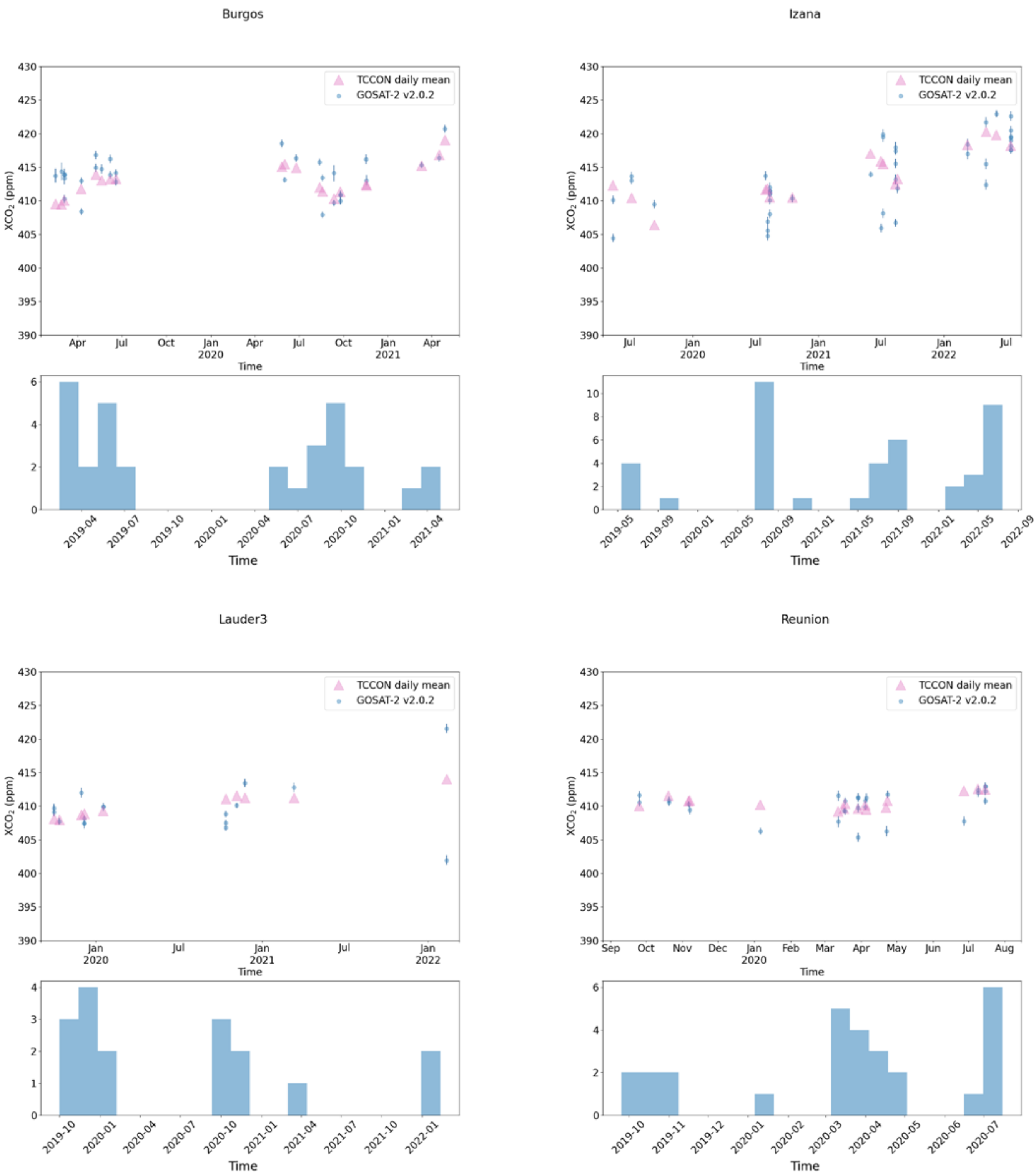



Figure 4 cont.

Figure 4 cont.

Figure 5: *Upper panels:* Timeseries for the individual stations for ocean soundings for CO2_GO2_SRFP. The pink triangles represent the daily average $XCO_2$ of the TCCON data and the blue circles are all the retrieved GOSAT-2 data. *Lower panels:* Histogram of number of GOSAT-2 retrievals in bins over the time range in question.



### 1.2.3 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<br>Level: 2, Version: 2.0.0, Time period covered: 02.2019 – 12.2022 | | | | |
|---|---|---|---|---|
| Parameter [unit] | Achieved performance | Requirement | TR | Comments |
| Single measurement precision (1-sigma) in [ppm] | 3.02 | < 8 (T)<br>< 3 (B)<br>< 1 (G) | - | - |
| Uncertainty ratio: Ratio reported uncertainty to standard deviation of satellite-TCCON difference | 0.78 | - | - | 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:<br>0.23 +/- 0.07<br>Spatiotemporal:<br>0.34 +/- 0.40 | < 0.5 | Probability that accuracy TR is met: 66 % | - |
| Stability: Drift [ppm/year] | 0.01 +/- 0.10 (1-sigma) | < 0.5 | Probability that stability TR is met: 99 % | - |
| Stability: Year-to-year bias variability [ppm/year] | 0.97 +/- 0.37 (1-sigma) | < 0.5 | - | - |

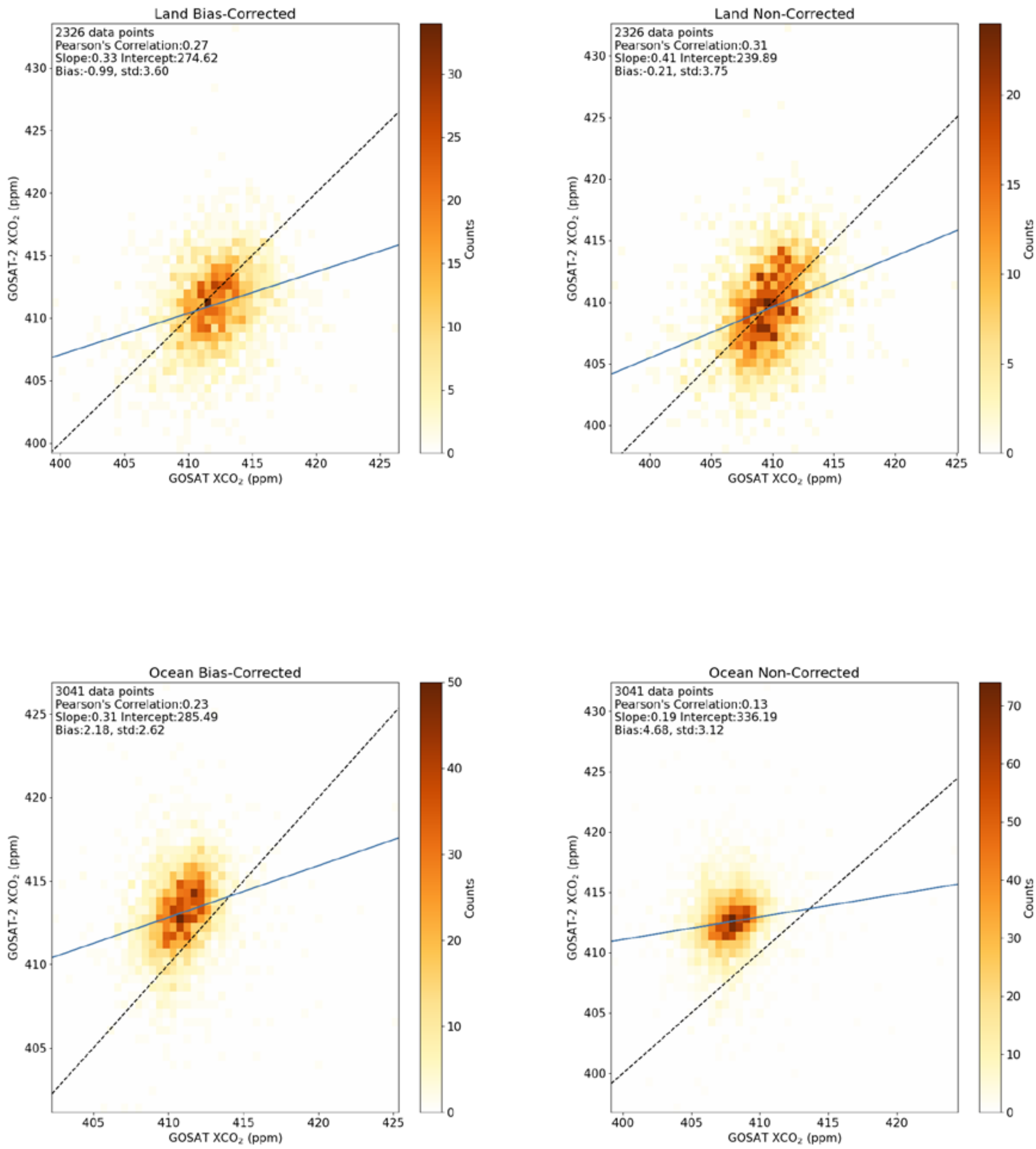
### 1.2.4 GOSAT-GOSAT2 Intercomparison

In this section we report on the comparison of the GOSAT-2 SRFP $XCO_2$ data versus co-located GOSAT-1. Figure 6 shows a comparison of GOSAT-2 and GOSAT FP-CO2 for both the non-corrected and bias-corrected 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 $CO_2$ products, where a bias correction based on the retrieved $O_2$ ratio (the ratio between retrieved and prior $O_2$ column) is used for GOSAT, whereas for GOSAT-2 the bias correction is based on the retrieved albedo at 1.6 um 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-$CO_2$ GOSAT vs GOSAT-2 for daily 1°x1° mean concentrations. Period covered is Feb 2019 to Dec 2022. 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 | 2326 | 2326 | 3041 | 3041 |
| Correlation | 0.27 | 0.31 | 0.23 | 0.13 |
| Bias [ppm] | -0.99 | -0.21 | 2.18 | 4.68 |
| Single measurement precision in ppm (std) | 3.60 | 3.75 | 2.62 | 3.12 |

Figure 6: Comparison of land and glint single soundings of SRFP-$CO_2$ with co-located GOSAT and GOSAT-2 measurements for the period 2019-2022, for bias corrected and non-bias corrected data. Bias and standard deviation values are given in ppm.



## 1.3 Product CH4_GO2_SRFP

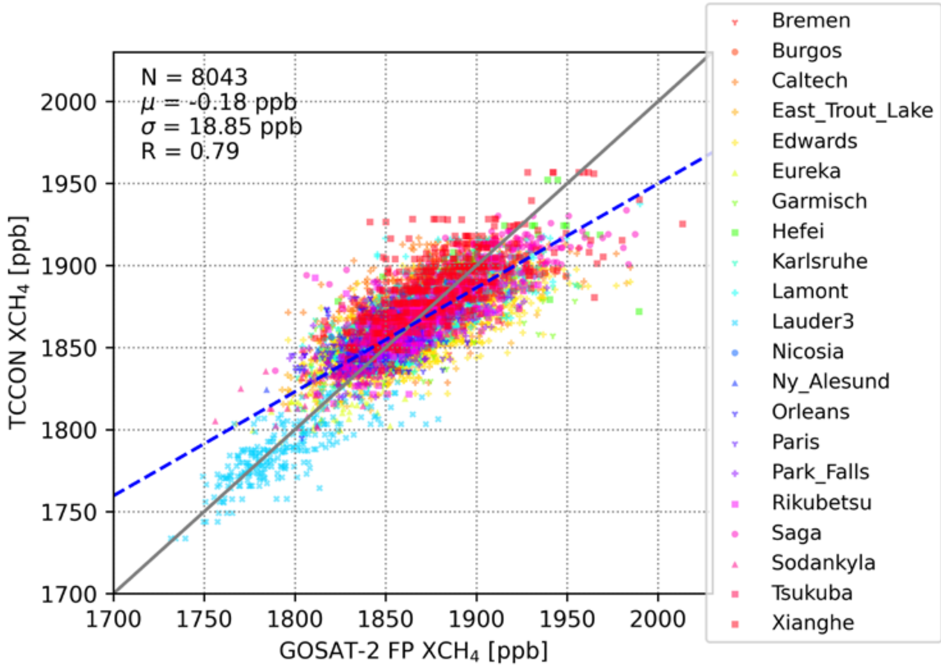
### 1.3.1 Validation

Figure 7 shows a very strong correlation of the retrieved (bias-corrected) $XCH_4$ with the TCCON $XCH_4$ (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 land observations, the station-to-station standard deviation is 3.0 ppb. As is the case for $CO_2$, Caltech/Edwards and Lamont show the largest number of observations and Ny Alesund the largest bias due to the low number of measurements. Lauder has a large remaining bias of ~ 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 2022. 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 $XCH_4$ 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 $XCH_4$ retrieved by GOSAT-2-RemoTeC with ground based TCCON measurements for land (top) and sunglint (bottom) soundings. N indicates the number of GOSAT-2-TCCON colocations, $\mu$ is the average difference (for individual measurements) between GOSAT-2 and TCCON, $\sigma$ the standard deviation of the GOSAT-2 TCCON difference (for individual measurements) and R the Pearson's correlation coefficient between the two set of observations.



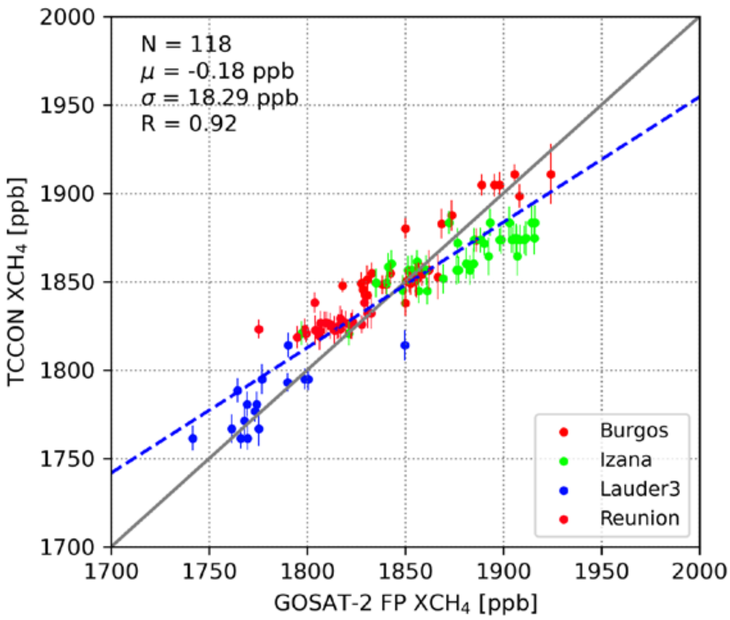



Figure 8: The bias, standard deviation and # of measurements per station for land (left) and sunglint (right) soundings for the period between the year 2019 and 2022.

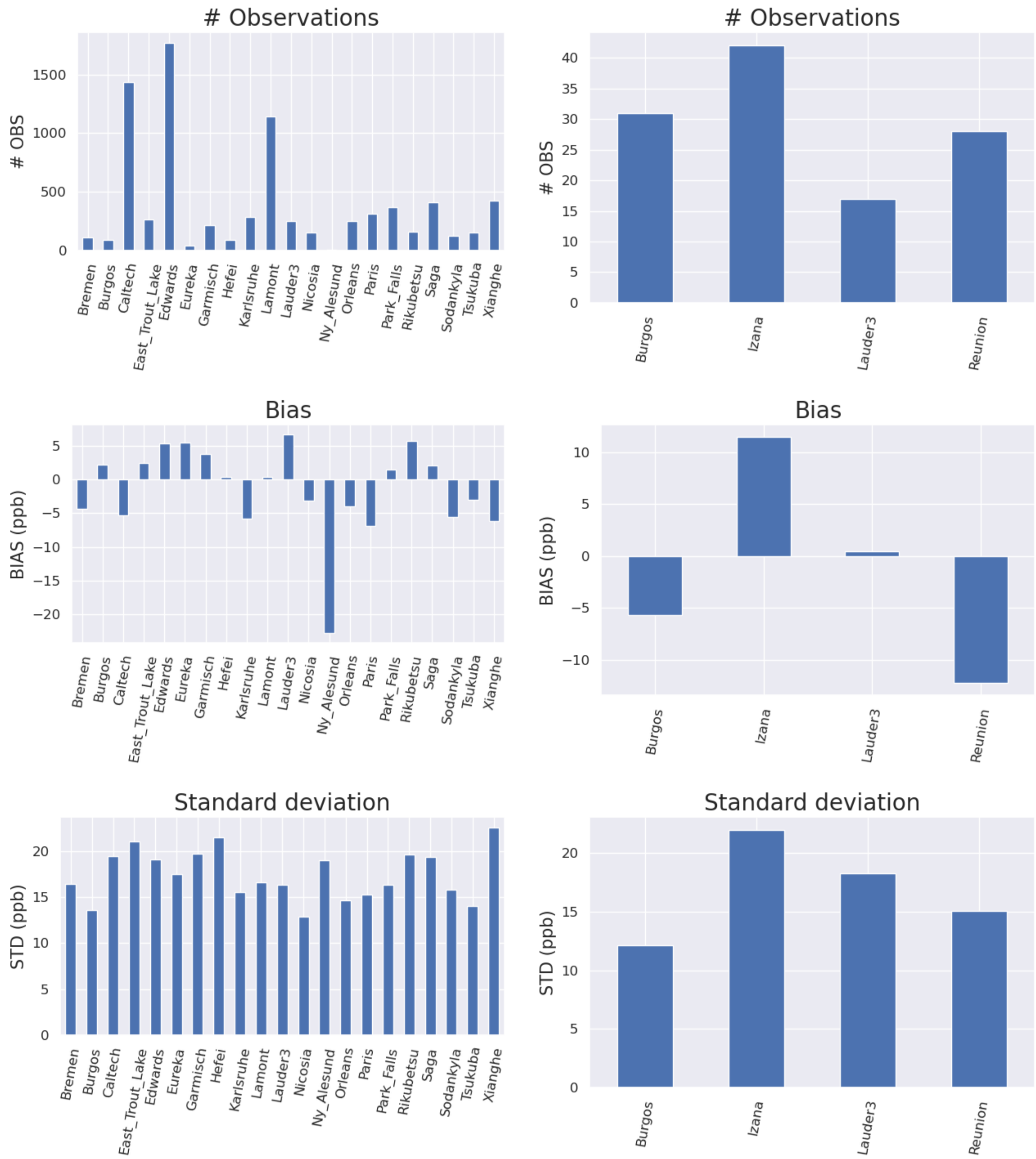
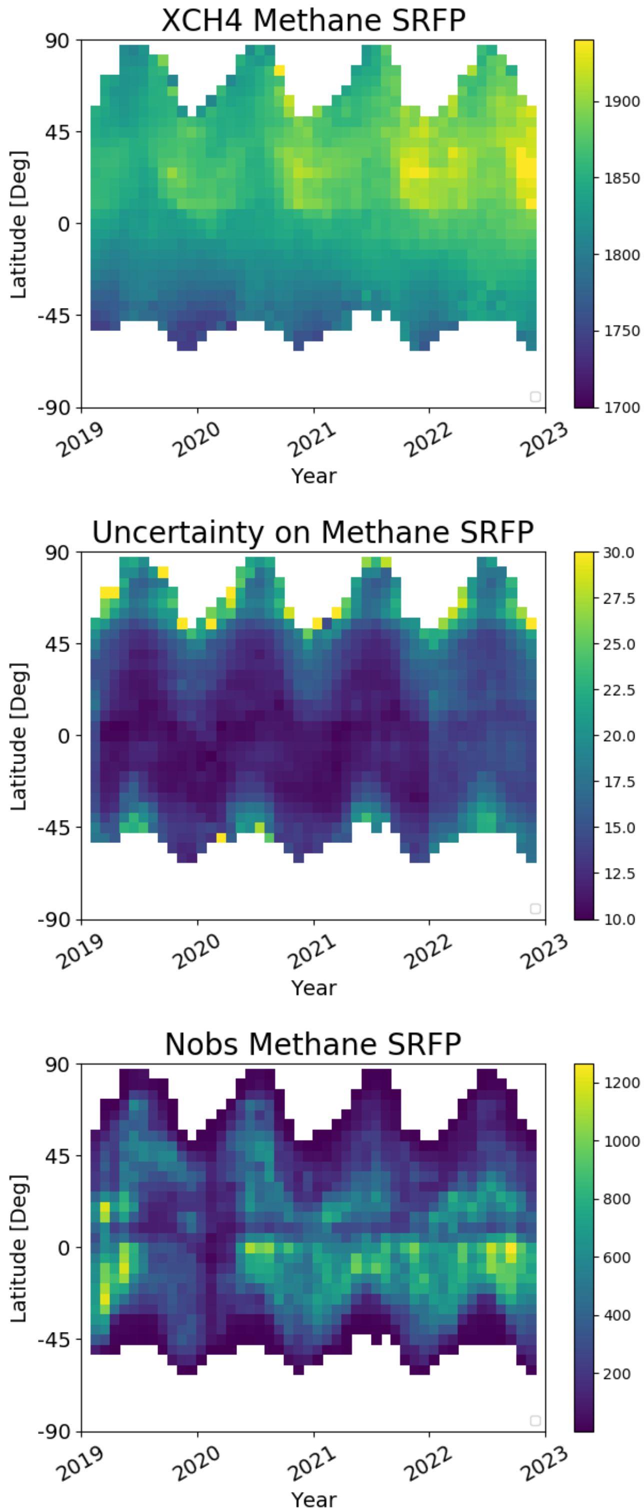


Figure 9: The CH4_GO2_SRFP global dataset in slices of 10 degrees latitude as a function of time. The increase in $XCH_4$ concentrations during the last couple of years can clearly be seen.



## 1.3.2 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: *Upper panels:* Timeseries for the individual stations for land soundings for CH4_GO2_SRFP. The pink triangles represent the daily average $XCH_4$ of the TCCON data and the blue circles are all the retrieved GOSAT-2 data. *Lower panels:* Histogram of number of GOSAT-2 retrievals in bins over the time range in question.

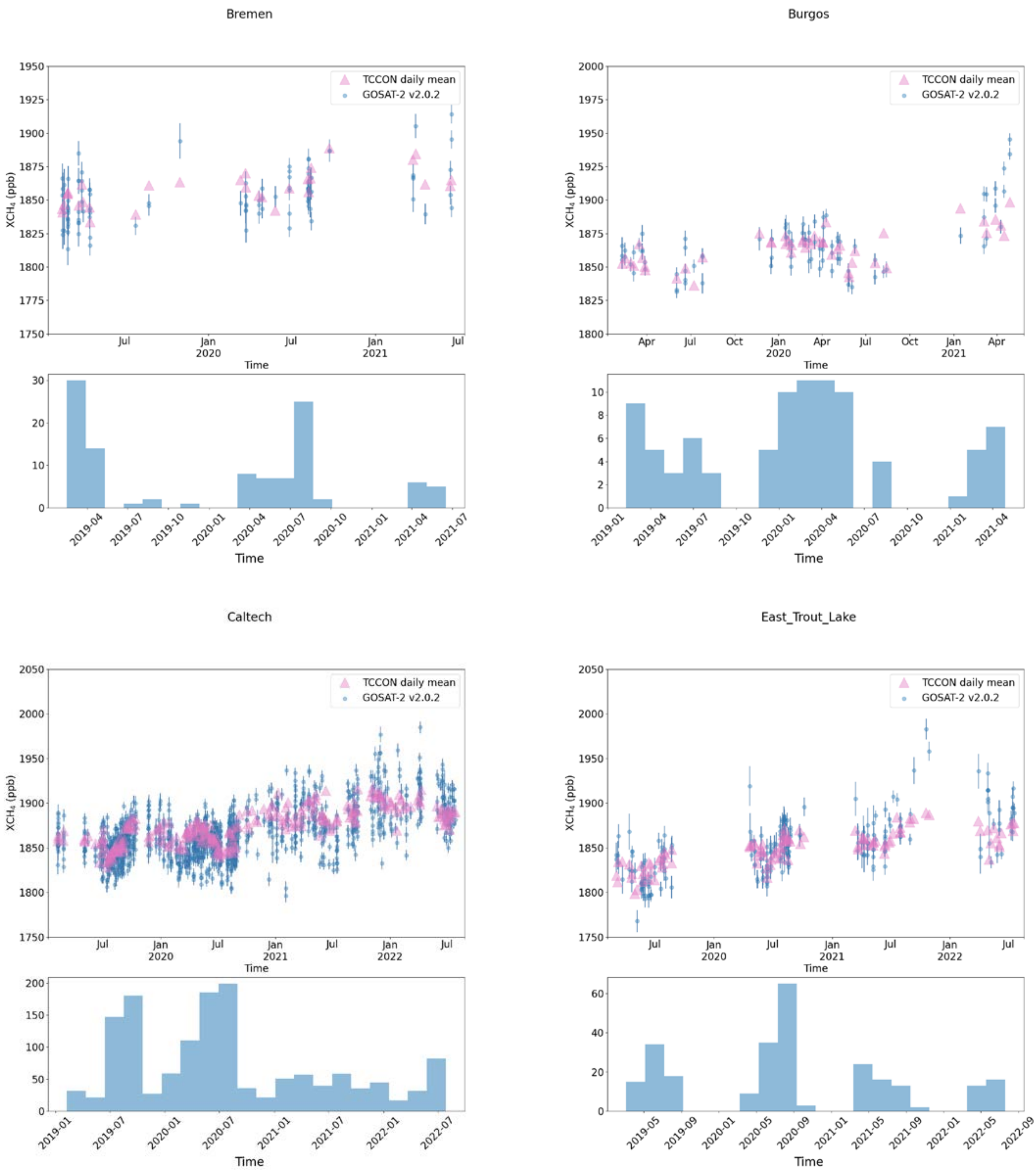


Figure 10 cont.

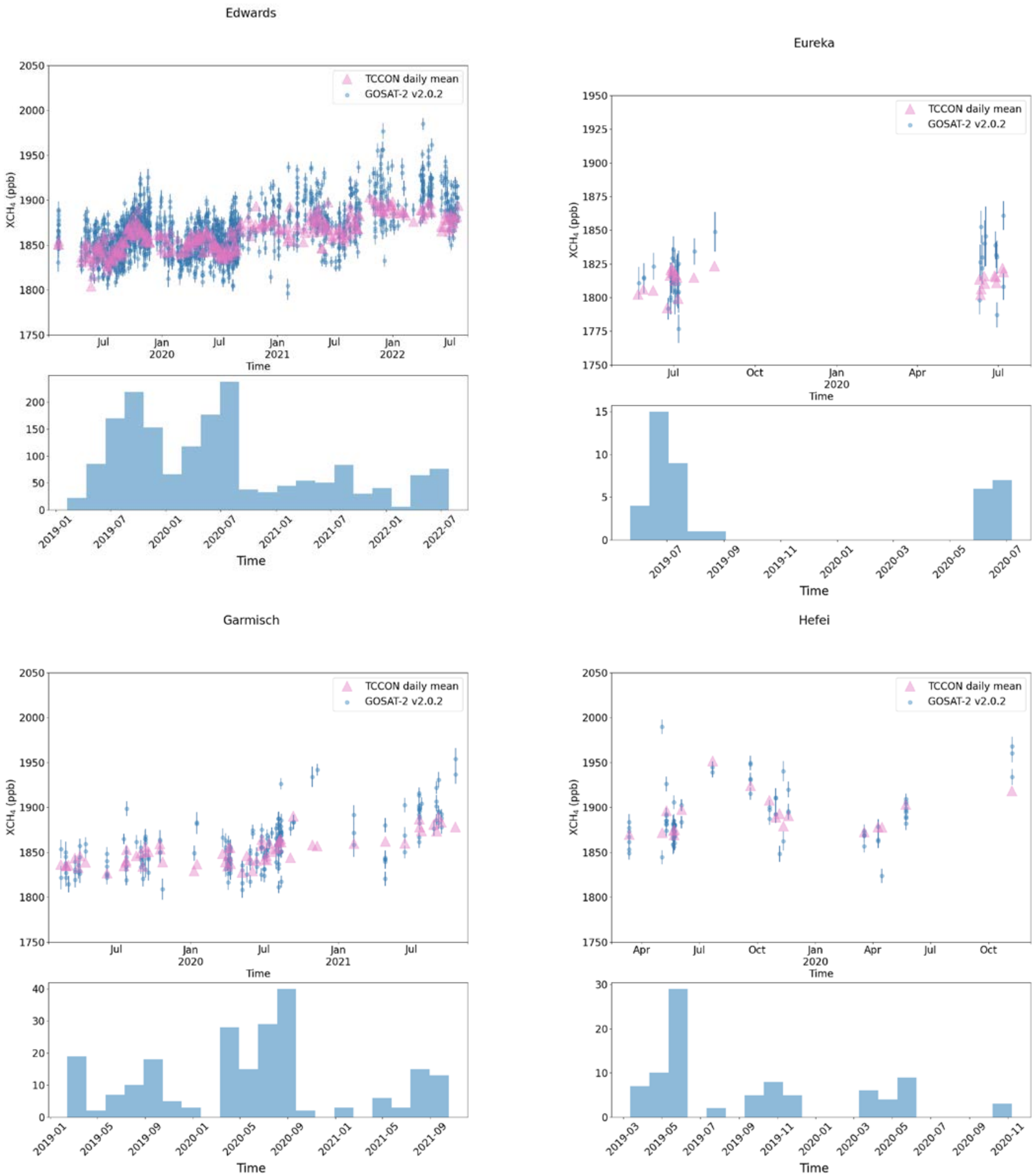


Figure 10 cont.

Figure 10 cont.

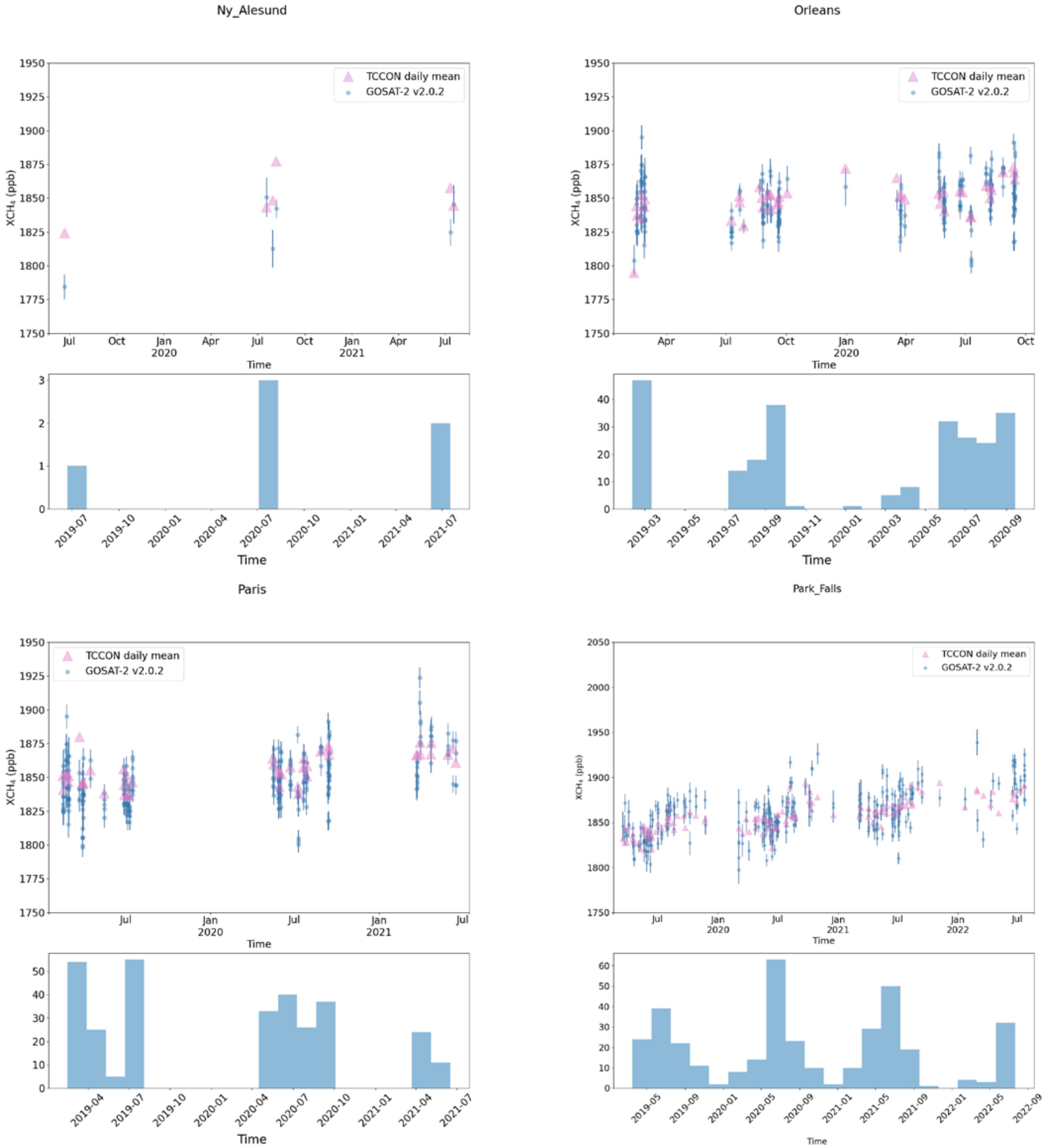


Figure 10 cont.

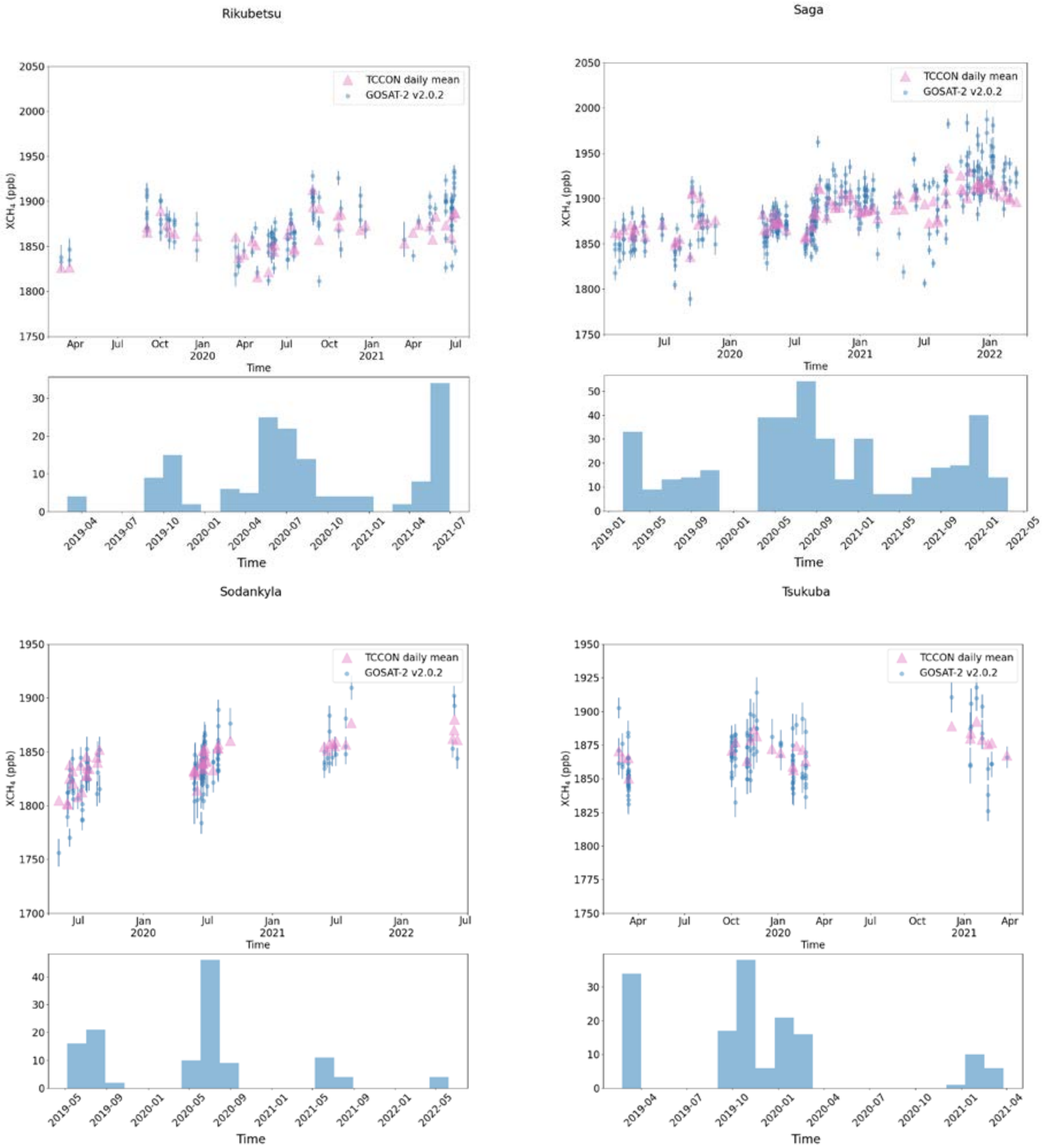


Figure 10 cont.

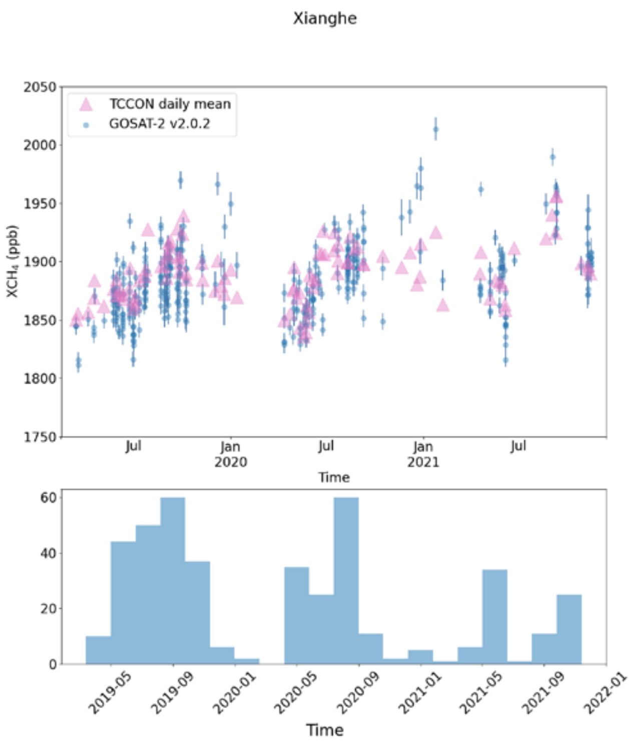
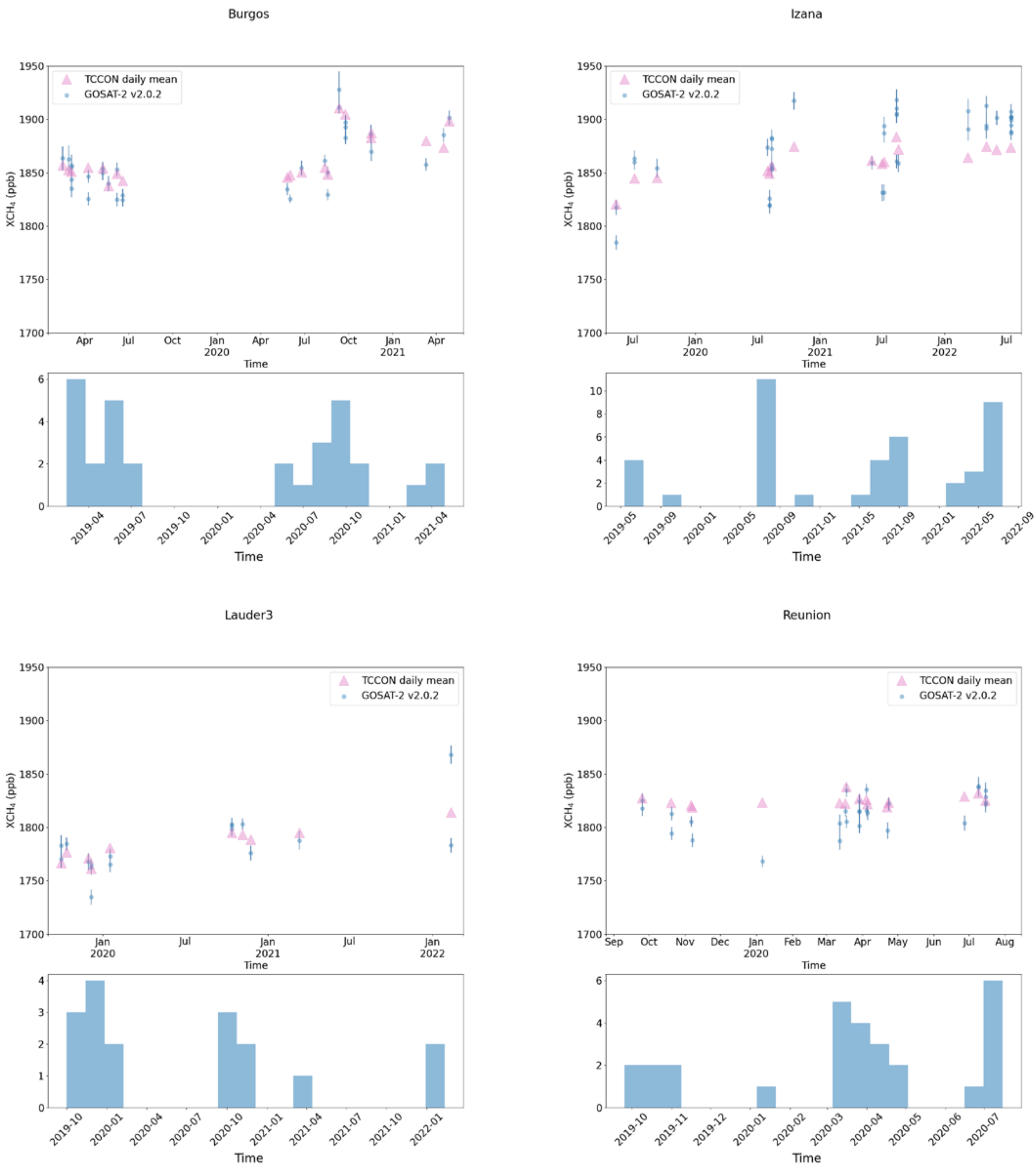


Figure 11: *Upper panels:* Timeseries for the individual stations for ocean soundings for CH4_GO2_SRFP. The pink triangles represent the daily average $XCH_4$ of the TCCON data and the blue circles are all the retrieved GOSAT-2 data. *Lower panels:* Histogram of number of GOSAT-2 retrievals in bins over the time range in question.



### 1.3.3 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<br>Level: 2, Version: 2.0.0, Time period covered: 02.2019 – 12.2022 | | | | |
|---|---|---|---|---|
| Parameter [unit] | Achieved performance | Requirement | TR | Comments |
| Single measurement precision (1-sigma) in [ppb] | 18.85 | < 34 (T)<br>< 17 (B)<br>< 9 (G) | - | - |
| Uncertainty ratio:<br>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] | -0.18 | - | - | No requirement but value close to zero expected for a high quality data product. |
| Accuracy: Relative systematic error [ppb] | Spatial:<br>1.62 +/- 0.37<br>Spatiotemporal:<br>3.00 +/- 1.97 | < 10 | Probability that accuracy TR is met: 99 % | - |
| Stability: Linear bias trend [ppb/year] | 0.79 +/- 0.52 (1-sigma) | < 3 | Probability that stability TR is met: 99% | - |
| Stability: Year-to-year bias variability [ppb/year] | 9.9 +/- 4.0 (1-sigma) | < 3 | - | - |

### 1.3.4 GOSAT-GOSAT2 Intercomparison

In this section we report on the comparison of the GOSAT-2 SRFP XCH4 data versus co-located GOSAT-1. Figure 12 shows a comparison of GOSAT-2 and GOSAT FP-CH4 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 standard deviation than the non-corrected version indicating that the random error is reduced with the bias correction. 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-CH4 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 land and glint single soundings of SRFP-$CH_4$ with co-located GOSAT and GOSAT-2 measurements for the period 2019-2022, for bias corrected and non-bias corrected data. Bias and standard deviation values are given in ppb.

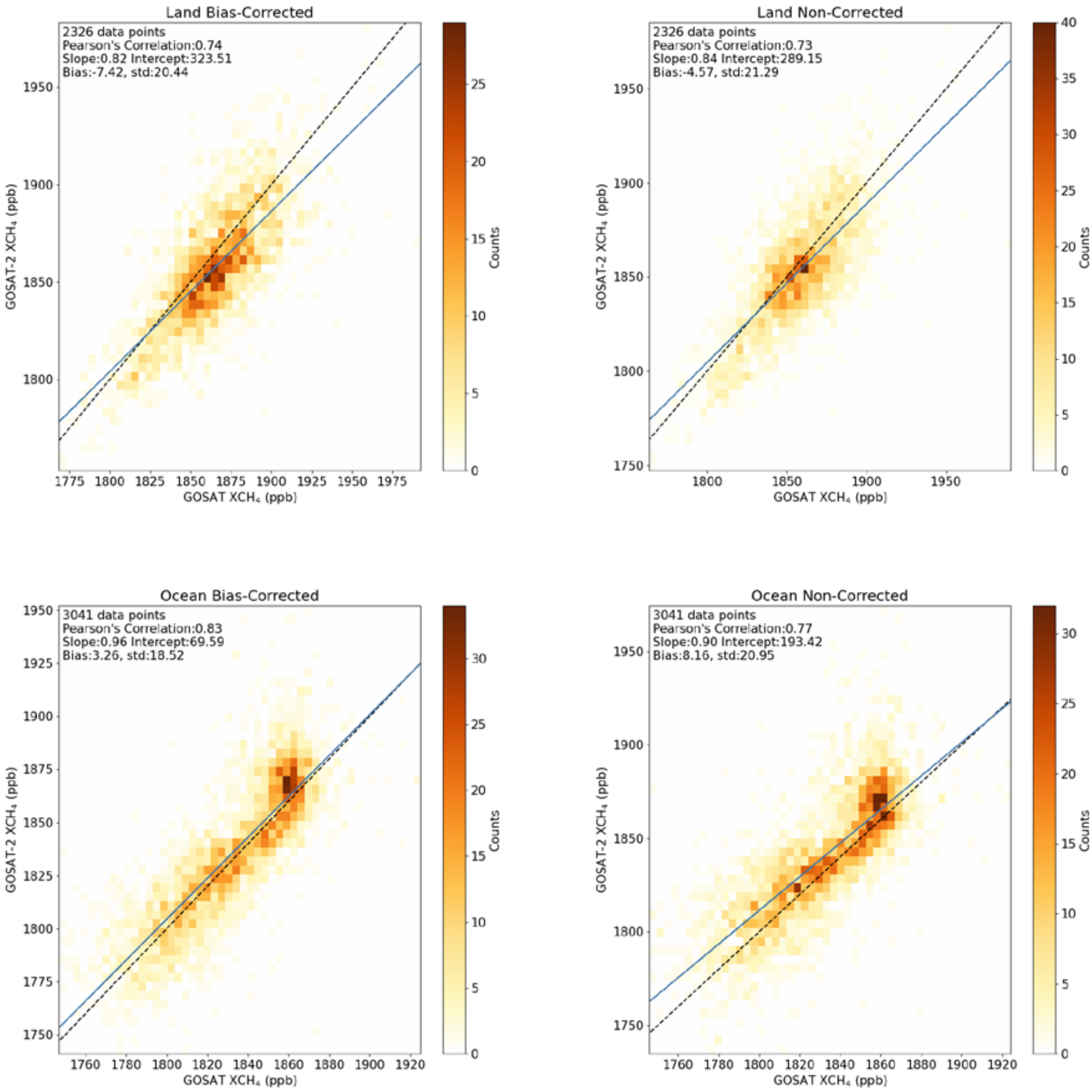


Table 4: Summary of the comparison of SRFP-$CH_4$ GOSAT vs GOSAT-2 for daily 1°x1° mean concentrations. Period covered is Feb 2019 to Dec 2022. The bias, standard deviation (precision), Pearson's correlation coefficient and number of observations (N) are given, for both the bias corrected and non-bias corrected values in land and glint mode.

| | Land | | Glint | |
|---|---|---|---|---|
| Parameter | Bias-Corrected | Non-corrected | Bias-Corrected | Non-Corrected |
| | | | | |
| N | 2326 | 2326 | 3041 | 3041 |
| Correlation | 0.74 | 0.73 | 0.83 | 0.77 |
| Bias [ppm] | -7.42 | -4.57 | 3.26 | 8.16 |
| Single measurement prescision in ppm (std) | 20.44 | 21.29 | 18.52 | 20.95 |

## Application(s) specific assessments

No application specific assessments have been carried out.

## Compliance with user requirements

For the CH4_GO2_SRFP product we reached a 99 % chance that the TR is met for accuracy and an 99 % chance the TR is met for stability. For CO2_GO2_SRFP we only reached a 66 % 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, 2016.

**JCGM, 2008:** JCGM/WG 1, Working Group 1 of the Joint Committee for Guides in Metrology, Evalutation of measurement data – Guide to the expression of uncertainty in measurement, 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 ($CO_2$ and $CH_4$) 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 ($CO_2$ and $CH_4$) 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), 2015.

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