



A consistent climate data record of atmospheric methane from the GOSAT and GOSAT-2 missions

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Abstract.

Understanding the renewed and accelerating growth of atmospheric methane requires satellite records that are long enough to span decadal change and consistent enough that instrumental differences are not mistaken for atmospheric signals. We present version 2.0 of the University of Leicester Proxy retrieval of column-averaged dry-air methane (XCH_4) from the GOSAT-



5 2 TANSO-FTS-2 instrument, comprising approximately 4.4 million quality-filtered soundings in land nadir and ocean glint
observation modes between 5 February 2019 and 31 December 2025. The data are processed with the same algorithm, a
priori fields, and quality-filtering framework as the established GOSAT Proxy v10.0 product, with the aim of producing a
consistent multi-instrument climate data record. The on-board intelligent pointing of GOSAT-2 improves the yield of usable
land soundings, particularly at coastal and island sites. The GOSAT-2 bias correction is cross-anchored to GOSAT over 124,206
10 matched-pair footprints and depends linearly on solar zenith angle. Anchoring to GOSAT rather than directly to the Total
Carbon Column Observing Network (TCCON) leaves the corrected GOSAT-2 with a residual mean TCCON bias of +5.52 ppb,
in exchange for sub-ppb inter-instrument consistency over the overlap period. Validation against the TCCON GGG2020.1
release yields a standard deviation of the satellite-minus-TCCON differences of 16.41 ppb and a correlation coefficient of
0.910 across 135,110 co-locations at 24 sites, compared to 16.42 ppb and 0.950 for GOSAT over 25 sites, demonstrating that
15 GOSAT-2 reaches the precision of the heritage instrument. Co-located monthly 2° grid-cell means from GOSAT and GOSAT-
2 during the 2019–2025 overlap correlate at 0.95 (land) and 0.97 (glint), with mean biases of +1.9 and +3.0 ppb. Beyond
the cross-anchored correction, no further adjustment for either observation mode is required to merge the two records. The
combined record forms a continuous Proxy XCH₄ time series spanning 2009 to 2025, which will be extended as both missions
continue to operate, and provides a reference for inter-comparison with TROPOMI and the next generation of greenhouse-gas
20 monitoring missions. The GOSAT-2 Proxy XCH₄ v2.0 dataset is available from the Centre for Environmental Data Analysis at
<https://doi.org/10.5285/8209b9acb92e4ba69188c9c8ff7a3b76> (Parker et al., 2026a).



1 Introduction

Atmospheric methane (CH_4) is the second most important anthropogenic greenhouse gas after carbon dioxide, with an estimated effective radiative forcing of 0.54 W m^{-2} since pre-industrial times (Forster et al., 2021).

25 Despite its importance, the processes controlling the global atmospheric methane budget remain poorly understood. After a period of near-zero growth from 1999 to 2006 (Dlugokencky et al., 2003; Rigby et al., 2008), atmospheric methane concentrations resumed their rise from 2007 onwards with signs of accelerated growth (Nisbet et al., 2019). An observed annual increase of 18 ppb in 2021 in the NOAA global surface record (Lan et al., 2022) was the largest since systematic measurements began (Feng et al., 2023; Jackson et al., 2024).

30 The most recent Global Methane Budget estimates total emissions of 575 [553–586] $\text{Tg CH}_4 \text{ yr}^{-1}$ for 2010–2019, of which approximately two-thirds are attributable to anthropogenic sources (Jackson et al., 2024; Saunio et al., 2025). The causes of the renewed growth and its recent acceleration remain actively debated. Proposed explanations include increased emissions from tropical wetlands (Nisbet et al., 2016; Feng et al., 2022; Qu et al., 2024), rising fossil fuel extraction (Schwietzke et al., 2016), and changes in the hydroxyl radical (OH) sink (Rigby et al., 2017; Turner et al., 2017). Peng et al. (2022) attributed the
 35 2020 methane surge in part to a reduction in OH driven by lower NO_x emissions during the COVID-19 pandemic alongside increased tropical wetland emissions, and Ciais et al. (2026) estimated that OH variability explains the majority of interannual growth rate variations between 2019 and 2023, with wetland and inland water emissions from tropical regions accounting for the remainder.

Satellite-based inversions using TROPOMI observations over 2019–2024 capture the same rise and subsequent decline, with
 40 global emissions increasing sharply in 2020–2021 and then falling towards their pre-2020 values (He et al., 2026). The isotopic record adds further complexity. The declining trend in $\delta^{13}\text{C-CH}_4$ that accompanied the post-2007 growth, consistent with a predominantly microbial source, appears to have flattened or reversed since 2023 (Nisbet and Manning, 2026). Resolving these competing and complementary hypotheses requires sustained, global observations of atmospheric methane with sufficient coverage to constrain regional emission estimates through inverse modelling.

45 Satellite remote sensing of atmospheric methane in the shortwave infrared (SWIR) has provided column-averaged dry-air mole fractions of methane (XCH_4) with global coverage since the launch of SCIAMACHY on Envisat in 2002 (Frankenberg et al., 2005, 2006). SCIAMACHY provided the first space-based maps of the global methane distribution, enabling early studies of regional methane sources (Bergamaschi et al., 2009, 2013). The Japanese Greenhouse gases Observing SATellite (GOSAT), launched in January 2009 with the TANSO-FTS instrument, extended and improved upon these observations with substantially
 50 higher spectral resolution in the CO_2 and CH_4 absorption bands around $1.6 \mu\text{m}$ (Kuze et al., 2009, 2016). The GOSAT series continues with GOSAT-2, launched in October 2018 and the subject of this work, and GOSAT-GW, launched in June 2025 (Imasu et al., 2023; Tanimoto et al., 2025). TROPOMI on Sentinel-5P, launched in October 2017 (Hu et al., 2016; Lorente et al., 2021), has since added methane observations with daily global coverage and finer spatial sampling, retrieving CH_4 from the $2.3 \mu\text{m}$ band. However, TROPOMI lacks accompanying CO_2 channels, so a Proxy-type retrieval (introduced below)
 55 is not possible from its measurements. The first of the Sentinel-5 instruments, launched on MetOp-SG-A1 in August 2025,



will extend these observations and, unlike TROPOMI, includes a 1590–1675 nm band covering the CO₂ channels required for Proxy-type retrievals.

Multiple retrieval algorithms (Butz et al., 2011; Schepers et al., 2012; Parker et al., 2011; Yoshida et al., 2013; Parker et al., 2020; Noël et al., 2022) have been applied to GOSAT and GOSAT-2 measurements to produce XCH₄ datasets. The two main approaches are either a Full-Physics or a Proxy retrieval. The Proxy and Full-Physics approaches represent fundamentally different strategies for dealing with atmospheric scattering. Full-physics retrievals model and fit the scattering explicitly, which can provide accurate results but at the cost of rejecting a larger fraction of observations where the scattering model is inadequate, including stricter filtering of scenes with higher aerosol optical depth. The Proxy approach, described below, avoids this problem by design, yielding a substantially higher fraction of quality-filtered retrievals.

The Proxy retrieval concept, first proposed by Frankenberg et al. (2005), exploits the fact that both CO₂ and CH₄ have absorption features of similar strength in the same spectral band near 1.6 μm, so that the ratio of the two retrieved columns largely cancels the common scattering and instrument errors and can be converted to XCH₄ using an independent model estimate of XCO₂ (Parker et al., 2011). The University of Leicester (UoL) implementation of this approach, its error characteristics, and its dependence on the modelled CO₂ are described in Sect. 3 and in detail by Parker et al. (2020).

The UoL GOSAT Proxy XCH₄ dataset has been used widely for studies of the global methane budget and regional emissions. Through the ESA Climate Change Initiative (CCI), the Copernicus Climate Change Service (C3S) and more recently the UK Earth Observation Climate Information Service (UK EOCIS), the data have been produced operationally and contributed to multi-algorithm ensemble products (Buchwitz et al., 2017; Reuter et al., 2020). The dataset has been used to constrain inverse models of the global methane budget (Saunois et al., 2020, 2025; Lu et al., 2021), to attribute the post-2006 growth in atmospheric methane (McNorton et al., 2018; Zhang et al., 2021), and to quantify regional emissions from North America (Maasakkers et al., 2019; Sheng et al., 2018), China (Zhang et al., 2022; Miller et al., 2019), tropical Africa (Lunt et al., 2019), South America (Wilson et al., 2021; France et al., 2022; Tunnicliffe et al., 2020), and India (Ganesan et al., 2017). It has also been combined with TROPOMI observations to produce blended methane products with improved spatial and temporal coverage (Balasus et al., 2023). Recent studies, including Qu et al. (2022), Feng et al. (2023) and Qu et al. (2024), used GOSAT observations to attribute the 2020 methane surge to wetland inundation in the tropics. In Parker et al. (2022) we used the data to evaluate wetland methane emissions in the Joint UK Land Environment Simulator (JULES) land surface model and in Folberth et al. (2022) we assessed the interactive wetland methane emission capability in the UK Earth System Model. A detailed review of the scientific applications of the data is given in Parker et al. (2020).

While much of the recent methane budget debate has focused on tropical sources, the Arctic and boreal regions also present important and distinct challenges. Thawing permafrost and northern wetlands are potentially large and climate-sensitive methane sources, yet they remain poorly constrained by current observing systems (Bartsch et al., 2025). Satellite remote sensing of methane at high latitudes is inherently difficult. Severe cloud cover, high solar zenith angles, low surface reflectance over snow and ice, and prolonged polar darkness all act to reduce the number of successful retrievals, creating a pronounced winter data deficit. The standard quality filtering applied to GOSAT retrievals, which is optimised for global data throughput, disproportionately rejects high-latitude observations. Bharathan et al. (2026) addressed this by developing a multi-objective



genetic algorithm approach to optimise the post-retrieval quality filtering of the UoL GOSAT Proxy XCH₄ dataset specifically for the high latitudes, increasing valid observations by up to 20% with less than 1 ppb loss in single-measurement precision and more than doubling the data available in December. At the same time, the blended TROPOMI+GOSAT product of Balasus et al. (2023) helps to fill spatial gaps by combining the accuracy of the GOSAT Proxy retrieval with the dense coverage of TROPOMI. The largest corrections in that product occur at high northern latitudes, where snow and ice surfaces can cause TROPOMI retrieval biases. Together, these developments highlight both the value of the long GOSAT time series and the ongoing need to improve satellite methane coverage in the Arctic and boreal zone. The improved signal-to-noise performance of GOSAT-2's TANSO-FTS-2 instrument reduces single-sounding uncertainty everywhere, and is especially valuable for the low-signal scenes of high-latitude winter (Sect. 2.1), offering one route to easing these limitations.

GOSAT-2, the follow-on to GOSAT, carries the TANSO-FTS-2 instrument, which extends the spectral coverage and targeted-observation capability of its predecessor (Suto et al., 2021; Imasu et al., 2023). In this work, we present the UoL GOSAT-2 Proxy XCH₄ dataset, covering the period from early 2019 to the end of 2025. The retrieval builds on the same algorithm described in Parker et al. (2020) for GOSAT, adapted for the GOSAT-2 TANSO-FTS-2 instrument. We describe the GOSAT-2 Proxy retrieval and its differences from the GOSAT processing chain, validate the GOSAT-2 data against the Total Carbon Column Observing Network (TCCON; Wunch et al., 2011a), identify and resolve a retrieval bias dependent on solar zenith angle (SZA) through a cross-anchored empirical correction, characterise the global XCH₄ distribution observed by GOSAT-2, and demonstrate the consistency between the GOSAT and GOSAT-2 records over their overlap period to support their use as a combined long-term climate data record spanning 2009 to present.

The paper is structured as follows. Section 2 describes the GOSAT-2 TANSO-FTS-2 instrument and its observation modes. Section 3 gives an overview of the UoL Proxy retrieval algorithm as applied to GOSAT-2, including quality filtering and retrieval throughput. Section 4 introduces the reference datasets, the GOSAT Proxy record and TCCON, and the co-location samples that link them to GOSAT-2. Section 5 derives the bias correction for both instruments. Section 6 characterises the temporal coverage and global spatial distribution of the dataset. Section 7 validates the retrievals against TCCON. Section 8 compares the GOSAT-2 and GOSAT records during their period of overlap and assesses the consistency of the combined climate data record. Finally, we provide a summary and outlook. The appendices contain supporting material for data users, including a summary of dataset characteristics, data contents and usage notes, and guidance on applying the GOSAT-2 averaging kernels to model fields.

2 GOSAT-2 TANSO-FTS-2 observations

GOSAT-2 was launched on 29 October 2018 by the Japan Aerospace Exploration Agency (JAXA), the Ministry of the Environment (MOE), and the National Institute for Environmental Studies (NIES) as the successor to the GOSAT mission (Suto et al., 2021). Like GOSAT, it carries a Fourier transform spectrometer, the Thermal And Near infrared Sensor for carbon Observation Fourier Transform Spectrometer 2 (TANSO-FTS-2), and a cloud and aerosol imager (CAI-2). The satellite operates in a sun-synchronous orbit at 613 km altitude with an equatorial overpass time of 13:00 ± 00:15 local time, matching that of



GOSAT. Its orbital path was chosen to lie between existing GOSAT tracks, so the two instruments together sample a denser set of ground locations than either provides alone. Key mission parameters are compared in Table 1.

2.1 Instrument capabilities and differences from GOSAT

TANSO-FTS-2 uses the same double-pendulum interferometer design as TANSO-FTS, with a maximum optical path difference of ± 2.5 cm and a spectral sampling interval of 0.2 cm^{-1} (Kuze et al., 2009; Suto et al., 2021). The field of view is unchanged at 15.8 mrad, but the lower orbital altitude reduces the ground footprint diameter from 10.5 km (GOSAT) to 9.6 km. Both instruments measure two linear polarisations (P and S) simultaneously for each SWIR band using a polarising beam splitter and two detectors.

Several changes were made to the instrument design. TANSO-FTS-2 has five spectral bands rather than four. Bands 1–3 cover similar SWIR wavelength ranges to GOSAT with optimised spectral windows. Band 1 has been extended towards shorter wavelengths, widening the window available for solar-induced fluorescence measurements. Band 2 (1.56–1.69 μm) contains the CO_2 and CH_4 absorption features used for the Proxy retrieval, corresponding to 5900–6400 cm^{-1} . Band 3 has been extended to 2.33 μm , adding a carbon monoxide (CO) absorption feature that was not accessible to GOSAT. The thermal infrared region is split across two bands (4 and 5) rather than one, which improves the signal-to-noise ratio (SNR) in this wavelength range. TANSO-FTS-2 uses photovoltaic mercury cadmium telluride (PV-MCT) detectors for bands 2 and 3, replacing the indium gallium arsenide (InGaAs) detectors used in TANSO-FTS.

Table 1. Comparison of GOSAT TANSO-FTS and GOSAT-2 TANSO-FTS-2 instrument specifications. Adapted from Suto et al. (2021).

Parameter	GOSAT TANSO-FTS	GOSAT-2 TANSO-FTS-2
Launch date	23 Jan 2009	29 Oct 2018
Orbit altitude	666 km	613 km
Revisit cycle	3 days (44 paths)	6 days (89 paths)
Footprint diameter	10.5 km	9.6 km
Field of view	15.8 mrad	15.8 mrad
Spectral sampling interval	0.2 cm^{-1}	0.2 cm^{-1}
SWIR bands	3	3 (Band 3 extended)
TIR bands	1	2
Gain settings	3	16
Cross-track points	5 (reduced to 3)	5
Intelligent pointing	No	Yes

The SNR has been improved across all three SWIR bands, primarily through a larger aperture and the optimised spectral ranges (Suto et al., 2021). Higher SNR translates directly into lower posterior retrieval errors. This improvement is particularly relevant at high northern latitudes in winter, where low solar elevation and surface albedo limited the quality of GOSAT



retrievals (Bharathan et al., 2026). A further practical change is the increase from 3 to 16 available gain settings, which allows the gain to better match the radiance level of each scene. On GOSAT, the instrument used a single high-gain mode for most soundings, with a medium-gain mode reserved for bright desert surfaces and a low-gain mode that is not used for science observation. On GOSAT-2, the gain varies by band and polarisation and is adjusted geographically (Orr, 2026, Ch. 3). Because the CH₄ and CO₂ retrieval windows lie within the same band and share the same gain state, the Proxy retrieval approach is largely insensitive to the gain configuration.

2.2 Observation modes and sampling strategy

Both instruments take observations over a 4-second integration period using a cross-track scanning pattern. GOSAT initially measured 5 cross-track points per row but this was reduced to 3 in August 2010 because of pointing-system stability issues. To date, GOSAT-2 retains 5 cross-track points. GOSAT could replace a limited number of lattice points with specified (targeted) observation locations. GOSAT-2 extends this capability so that lattice points can be replaced entirely, allowing increased sampling of megacities, emission hotspots, and ground validation sites. During the GOSAT mission this targeting strategy was extended to preferentially select coastal and island sites whilst avoiding bays and channels, increasing the yield of high-quality retrievals at land-surface footprints (Kuze et al., 2016).

The revisit cycle is 6 days (89 orbital paths) for GOSAT-2, compared to 3 days (44 paths) for GOSAT. This means GOSAT-2 provides wider geographic coverage between successive orbital tracks, but at the cost of fewer repeat observations along each track. Every 6 days, the GOSAT and GOSAT-2 orbital paths come into alignment, producing near-coincident soundings that can be co-located for direct comparison with tight spatial and temporal criteria (Orr, 2026). See Sect. 8 of this work for further details.

GOSAT-2 includes an intelligent pointing mechanism that was not available on GOSAT (Suto et al., 2021). Before each sounding, an on-board RGB camera acquires an image of a 50 km × 30 km area around the planned observation point. If clouds are detected, the pointing mirror is steered to a cloud-free area within this field, with the full sequence completed in 650 ms. This reduces the fraction of cloud-contaminated soundings before any ground processing is applied, and is most effective over persistently cloudy tropical regions such as central Africa, the Amazon, and Southeast Asia. The mechanism operates for land observations and is not used in the sun-glint mode.

Over water surfaces, where reflectance is generally low, both instruments observe in a sun-glint geometry to exploit specular reflection. The glint observations are restricted to a latitude band that varies seasonally with solar angle.

2.3 Instrument anomalies and data gaps

The GOSAT-2 record contains several multi-day suspensions of TANSO-FTS-2 observation that are noticeable in the monthly sounding counts (Sect. 6.1). The largest are two orbit-control campaigns, an inclination-control campaign from 20 September to 11 October 2021 and an out-of-plane campaign from 10 May to 7 June 2024, each suspending observations for three to four weeks. The remaining interruptions, including two unplanned debris-avoidance manoeuvres in April 2019 (Suto et al., 2021), routine orbit maintenance, and autonomous protective transitions to safe or diagnostic modes, each lasted between three and



ten days. The impact on the dataset is a reduction in the number of available soundings during the affected months rather than any systematic change in retrieval quality for the soundings that are obtained, and we exclude no data on the basis of these events beyond the standard quality filtering described in Sect. 3.3. The history of these operational events is summarised in Appendix I.

180 3 UoL Proxy XCH₄ retrieval

The UoL Proxy XCH₄ retrieval applied to GOSAT-2 follows the same approach as described in Parker et al. (2020) for GOSAT. The method was first proposed by Frankenberg et al. (2005) and has been applied to GOSAT data through a series of product versions (Parker et al., 2011, 2015, 2020). Here we describe the processing chain as applied to GOSAT-2, noting where it differs from the GOSAT implementation.

185 The Proxy retrieval exploits the fact that CO₂ and CH₄ both have absorption features within the same spectral band near 1.6 μm. Because atmospheric scattering and instrument effects influence the two gases in a similar way, taking the ratio of the retrieved column amounts largely cancels these common errors (Frankenberg et al., 2005; Parker et al., 2011). The dominant such errors are modification of the light path by aerosol and thin cirrus scattering, together with radiometric and calibration effects that act on both gases alike. Because the cancellation applies only to effects common to the two fit windows, the main errors remaining after the ratio are the dependence on the model XCO₂ (Sect. 3.4), spectroscopic uncertainties, and any spec-
 190 trally structured effects that differ between the CH₄ and CO₂ windows, such as the wavelength-dependent polarisation response discussed in Sect. 5 (Parker et al., 2020). The Proxy XCH₄ is then recovered by multiplying this ratio by an independent model estimate of XCO₂:

$$\text{XCH}_{4\text{Proxy}} = \frac{\text{XCH}_{4\text{retrieved}}}{\text{XCO}_{2\text{retrieved}}} \times \text{XCO}_{2\text{model}}. \quad (1)$$

195 The main advantage of this approach over Full-Physics retrievals is that it avoids the need to model atmospheric scattering explicitly, yielding a much higher fraction of successful retrievals. The trade-off is a dependence on the accuracy of modelled XCO₂, though the relative variability of atmospheric CO₂ is small compared to that of CH₄, so the errors introduced are modest. Parker et al. (2020) provides a detailed discussion of the associated uncertainties.

3.1 Retrieval inputs and a priori generation

200 The retrieval uses GOSAT-2 Level 1B (L1B) calibrated spectra, version V220.220 for 2019–2023 and V220.221 for 2024–2025 (differences between these subversions have no impact on the spectral regions used in this study), distributed by JAXA via the GOSAT-2 Product Archive (NIES, 2026). These contain radiometrically calibrated spectra, derived from the measured interferograms, along with geolocation, satellite geometry, and per-sounding quality information. The L1B data cover the period from 5 February 2019 to the end of December 2025 for this work.

205 Spectra are preprocessed using the Leicester Retrieval Preparation Tool (LRPT), which prepares the input data for the retrieval and estimates the per-sounding noise using the instrument conversion tables and degradation model. The preprocessing



steps are the same as those applied in the GOSAT processing chain, adapted for differences in the GOSAT-2 L1B file format and band definitions.

Consistent with our GOSAT retrieval, a priori profiles of CH₄ are generated from the MACC-II reanalysis fields combined with TOMCAT chemical transport model (CTM) output. CO₂ a priori profiles are drawn from the Copernicus Atmosphere Monitoring Service (CAMS) greenhouse gas reanalysis (Agustí-Panareda et al., 2023). Temperature and water vapour profiles are taken from ERA5 reanalysis (Hersbach et al., 2020). Spectroscopic line parameters for CO₂, H₂O, and O₂ are taken from version 4.2.0 of the OCO line lists, and CH₄ line parameters are taken from the TCCON line lists (Toon, 2015a). The solar reference spectrum is the same as that used in the GOSAT Proxy retrieval (Toon, 2015b).

The instrument-specific parts of the input chain are the L1B data source with its associated file format handling, the GOSAT-2 instrument line shape, and the GOSAT-2 noise estimation. All a priori fields, spectroscopic databases, and auxiliary data are the same as those used in the corresponding GOSAT v10.0 product (Parker et al., 2020, 2026b), reducing the risk of introducing inconsistencies or biases between the two datasets.

3.2 Cloud screening

Cloud screening is performed using a surface pressure test based on the O₂ A-band (Band 1). A retrieval of apparent surface pressure from the O₂ A-band (the retrieval neglects scattering by aerosol and cloud) is compared against the expected surface pressure from the meteorological prior (ERA5). Soundings for which the retrieved surface pressure deviates from the prior by more than a defined threshold of 30 hPa are flagged as cloud-contaminated and rejected. This approach detects both optically thick clouds and scenes with significant aerosol scattering that would compromise the accuracy of the SWIR retrieval.

The intelligent pointing system on GOSAT-2 steers soundings towards cloud-free ground within each scene before acquisition (Sect. 2.2), although the cloud-free fraction of the acquired soundings remains comparable to that of GOSAT (Sect. 3.5). The surface pressure test remains necessary to catch cloud contamination and thin cirrus that the on-board camera cannot detect.

3.3 XCH₄ and XCO₂ retrievals

The spectral fitting follows an optimal estimation framework (Rodgers, 2000; Connor et al., 2008). XCH₄ and XCO₂ are retrieved simultaneously from Band 2 of the GOSAT-2 TANSO-FTS-2 spectrum in the 1.6 μ m region. The state vector includes column scaling factors for CH₄ and CO₂, surface albedo and its spectral slope, and a spectral dispersion quantity (a spectral shift and stretch). The forward model simulates the top-of-atmosphere radiance for a given atmospheric state and compares it to the measured spectrum. The state vector is then iteratively updated to minimise the cost function (see Parker et al., 2020, for the full mathematical formulation). To characterise the quality of the spectral fit across the record, we average the fit residual over all quality-filtered soundings. The resulting mean GOSAT-2 fit is shown in Fig. 1.

Averaging the spectral fit residual over the full quality-filtered record (2,114,108 GOSAT-2 and 3,985,669 GOSAT land soundings) suppresses the random measurement noise by approximately $\sqrt{N}$ and isolates the systematic part of the fit (Fig. 1; the GOSAT equivalent is shown in Fig. E1). The band-averaged mean residual is indistinguishable from zero, below 0.01 % of

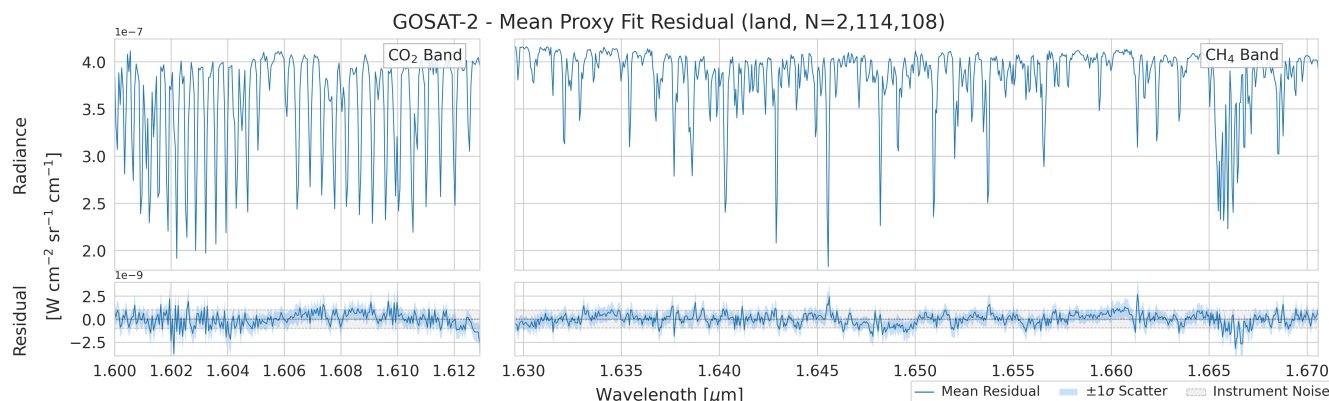


Figure 1. Mean GOSAT-2 Proxy fit over the full quality-filtered land record ($N = 2,114,108$ soundings). Top: mean measured radiance in the CO_2 (left) and CH_4 (right) retrieval windows. Bottom: mean fit residual (measured minus forward model), with the mean single-sounding instrument noise (shaded) and the $\pm 1\sigma$ inter-sounding scatter. Radiances are in $\text{W cm}^{-2} \text{ sr}^{-1} \text{ cm}^{-1}$. Averaging over ~ 2 million soundings suppresses the random noise and isolates the systematic, line-correlated residual structure discussed in the text.

240 the continuum radiance in both bands and for both instruments, so the retrieval is radiometrically unbiased. What remains is structured rather than random, with a root-mean-square (RMS) amplitude of 0.13–0.22 % of the continuum radiance for both bands, both instruments and both observation modes. This amplitude is comparable to the single-sounding instrument noise (the shaded band in Fig. 1), so the individual fits are close to noise-limited. The spatial distribution of the fit χ^2 is shown in Fig. 2.

245 This structure is concentrated at the absorption lines. The residual RMS at the deepest absorption pixels exceeds that of the line-free continuum by a factor of 1.3 to 1.8, but it correlates only weakly with absorption depth ($|r| < 0.15$) or with the local spectral gradient ($|r| < 0.15$), and a linear combination of the two explains almost none of its variance ($R^2 < 0.03$). It is therefore not a uniform scaling of the line strengths, nor a global wavelength-registration error, but a set of sign-varying, line-specific residuals of the kind expected from errors in the spectroscopic line parameters and in the modelled instrument line
 250 shape.

The mean residual is also highly reproducible. Individually for both GOSAT and GOSAT-2 its shape is almost identical between the land and glint retrievals (Pearson correlation coefficient $r = 0.94$ to 0.97 across the two bands), even though the two modes sample very different surfaces, albedos, viewing geometries and aerosol loadings. It is also correlated between the two independent instruments over their land records ($r = 0.46$ for the CO_2 band and $r = 0.74$ for the CH_4 band), as can be
 255 seen by comparing Figs. 1 and E1. A residual that is invariant to observing mode and shared between platforms is unlikely to arise mainly from scene-dependent effects or from instrument-specific calibration and line-shape errors, since neither would reproduce in this way. We therefore attribute it primarily to the components common to both retrievals, the forward model and the underlying CO_2 and CH_4 spectroscopy. This places a floor of roughly 0.2 % of the continuum on the achievable fit

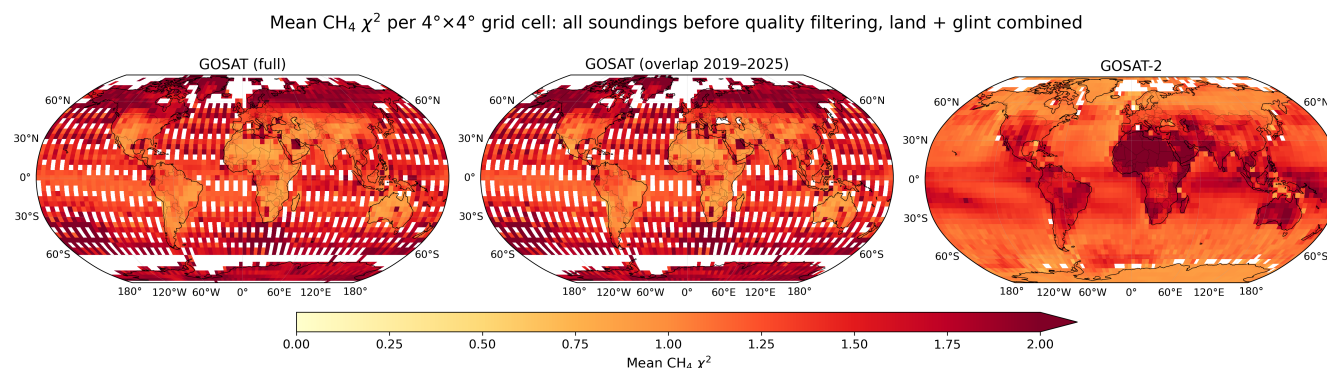


Figure 2. Global maps of the mean CH₄ spectral fit χ^2 statistic on a 4° grid for GOSAT (full record, left), GOSAT restricted to the GOSAT-2 overlap period 2019–2025 (centre), and GOSAT-2 (right). All retrieved soundings prior to quality filtering are included, with land and ocean glint observations combined. The spatial pattern reflects differences in scene complexity, surface type, and aerosol loading across the three datasets.

quality that improvements to cloud screening or radiometric calibration alone are unlikely to lower, and it points to updated spectroscopic line parameters as the most direct route to a closer fit.

After the spectral fit converges, post-retrieval quality filters are applied. These include spectral fit χ^2 bounds, posterior error limits, retrieved state plausibility checks, retrieval convergence and validity criteria, and a southern latitude cutoff. The full set of thresholds for both instruments is given in Appendix F. The quality filter thresholds were optimised against TCCON validation data following the same procedure described in Parker et al. (2020). Soundings that pass all filters are assigned a quality flag of 0 (“good”) and form the final dataset. The global spatial distribution of the mean χ^2 statistic for all retrieved soundings, prior to quality filtering, is shown in Fig. 2. The GOSAT-2 χ^2 values are generally higher than GOSAT. Because χ^2 normalises the fit residual by the instrument noise, the same absolute structured residuals produce a larger value against GOSAT-2’s smaller noise floor, a direct result of its higher SNR. The spatial distribution also shows elevated χ^2 over desert regions, more pronounced than in GOSAT. This may reflect the more complex 16-level gain structure of TANSO-FTS-2 under high-radiance conditions, and potentially warrants future investigation.

The processing chain is summarised as a Sankey flow diagram (Fig. 3) which highlights the throughput/dropoff in number of soundings at each processing step (total L1B soundings → cloud-screened → converged → quality-filtered). The throughput is quantified in Sect. 3.5.

3.4 Model XCO₂

The model XCO₂ used in Eq. (1) is calculated as the median of XCO₂ estimates from multiple chemical transport models, following the approach of Parker et al. (2020). Using the median of several models reduces the sensitivity to biases in any single model’s transport or surface flux distribution. The contributing models are the same set used for the GOSAT v10.0 Proxy product (Parker et al., 2026b): GEOS-Chem (Feng et al., 2011), NOAA CarbonTracker (Peters et al., 2007), and the



CAMS inversion system (Chevallier et al., 2011). The model XCO_2 is interpolated to the time and location of each GOSAT-2 sounding and integrated with the appropriate averaging kernel.

Because the atmospheric variability of CO_2 is much smaller in relative terms than that of CH_4 , errors in the model XCO_2 propagate into the Proxy XCH_4 at a reduced level. Parker et al. (2015) assessed the contribution of XCO_2 model uncertainty to the overall XCH_4 error budget and found it to be generally small compared to the retrieval error, though it can become a significant uncertainty component during summer months in some regions.

3.5 Retrieval throughput

The number of soundings retained at each processing stage measures the overall efficiency of the retrieval chain and the impact of the quality filters. Figure 3 shows this throughput as a flow diagram for both instruments, processed through the same chain, GOSAT over its full record (April 2009 to December 2025) and GOSAT-2 (February 2019 to December 2025). Of the 33,327,524 GOSAT and 16,549,175 GOSAT-2 L1B soundings, 7,750,465 (23.3 %) and 4,442,498 (26.8 %) respectively pass the full chain through to the final quality filter. GOSAT-2 has accumulated about half the GOSAT sounding total in under seven years of operation, against more than sixteen years for GOSAT. The intelligent pointing system (Sect. 2.2) increases the yield of soundings at coastal and island sites in particular. This advantage acts at the acquisition stage and not on the downstream cloud-free fraction, which is comparable for the two instruments.

Cloud screening is the dominant filter for both instruments. Only 36.8 % of GOSAT and 34.9 % of GOSAT-2 soundings are cloud-free, with the majority (54.8 % and 59.5 %, respectively) flagged as cloudy. The remaining stages remove comparatively little. Pre-processing succeeds for 99.6 % of GOSAT-2 soundings against 95.7 % for GOSAT, and methane is retrieved for almost all cloud-free soundings, with failed retrievals at most 0.2 % for either instrument. The final yield is therefore set by the cloud-free fraction together with the post-retrieval quality filter, which passes 77 % of retrieved GOSAT-2 soundings against 64 % for GOSAT. The net result is a slightly higher quality-filtered yield for GOSAT-2 (26.8 % against 23.3 %) despite a comparable cloud-free fraction, driven mainly by its more complete pre-processing and higher quality-filter pass rate.

4 Reference datasets and co-location

In addition to the GOSAT-2 product described above, the bias correction (Sect. 5) and validation (Sect. 7) draw on two reference data sources, the GOSAT Proxy XCH_4 record and the TCCON ground-based network, together with the co-location samples that link them to GOSAT-2.

4.1 GOSAT Proxy XCH_4 dataset

For the comparison with GOSAT-2, we use the UoL GOSAT Proxy XCH_4 v10.0 dataset (Parker et al., 2020, 2026b). This product covers the full GOSAT record considered in this study, April 2009 to December 2025 (the GOSAT-2 record spans February 2019 to December 2025), and is processed using the same retrieval algorithm, a priori fields, model XCO_2 , and quality filtering approach as the GOSAT-2 product described above. Relative to the v9.0 product described by Parker et al.

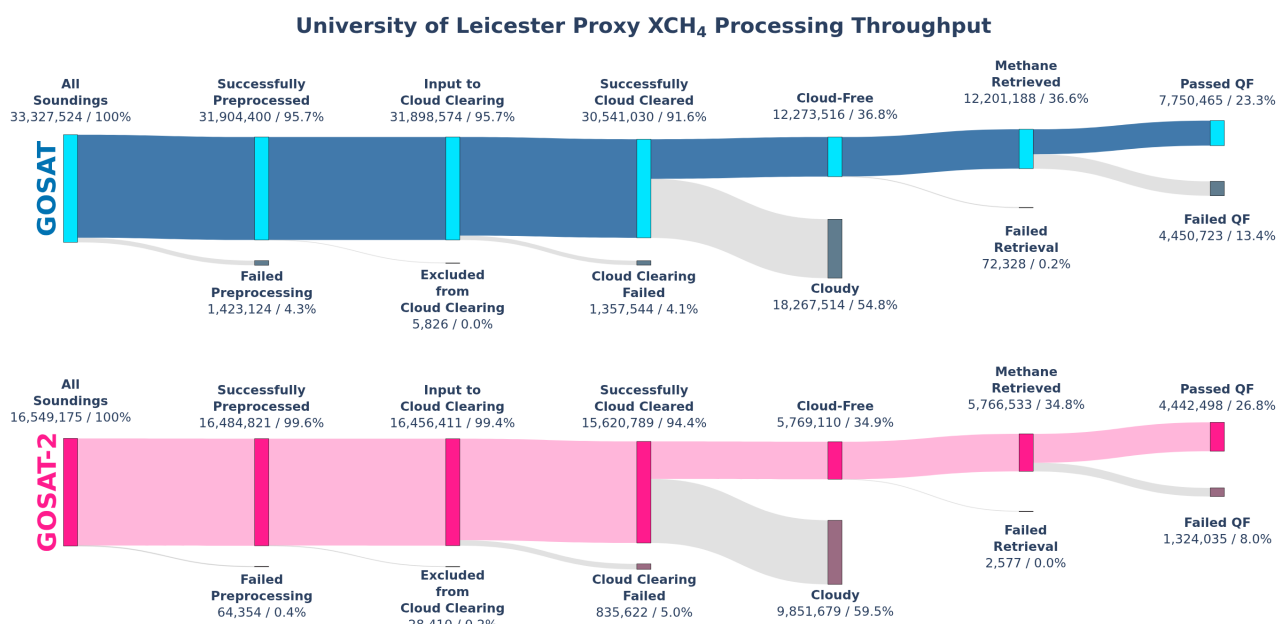


Figure 3. Sankey diagram of the retrieval processing throughput for GOSAT (top) and GOSAT-2 (bottom), processed through the same University of Leicester processing chain. The flow shows the number of soundings retained at each stage: LIB input, cloud screening, spectral convergence, and post-retrieval quality filtering. Percentages are relative to each instrument's total L1B soundings. Cloud screening is the largest single reduction at both instruments. GOSAT-2's higher quality-filtered yield (26.8 % against 23.3 %) comes mainly from more complete pre-processing and a higher quality-filter pass rate. Percentages are rounded independently and may not sum exactly.

(2020), v10.0 extends the record to December 2025 and re-derives the bias correction against the GGG2020 TCCON release rather than GGG2014 (Sect. 4.2); the processing chain is otherwise unchanged. The use of a common algorithm and processing chain for both instruments is a deliberate design choice that minimises methodological differences between the two datasets, so that any observed differences can be attributed to the instruments or sampling rather than to the retrieval.

4.2 TCCON

Validation uses TCCON (Wunch et al., 2011a), a network of ground-based high-resolution Fourier transform spectrometers that measure column-averaged dry-air mole fractions of several greenhouse gases including CH₄. The network continues to expand, with recently established sites such as Nicosia (Rousogonous et al., 2026) and Harwell (Weidmann et al., 2025) contributing to this work, and further sites planned at Kolkata (India) and Calakmul (Mexico) that would be particularly valuable for evaluating satellite data in the tropics. TCCON is the primary reference standard for satellite XCH₄ validation because of its high precision (~3.5 ppb for XCH₄) and traceability to the World Meteorological Organization (WMO) in situ scale through regular aircraft and balloon calibration campaigns. We use the GGG2020.1 release (Wunch et al., 2025; Total Carbon Column Observing



Network (TCCON) Team, 2026), distributed in the 2020.1.A file format and released on 19 June 2026 as a minor update of the original GGG2020 data version of April 2022. Relative to the earlier GGG2014 release, GGG2020 XCH₄ is approximately 5.3 ppb lower on average across the network, with the largest reductions at high-latitude sites. The shift is attributed primarily to improvements in the a priori profiles used in the retrieval (Wunch et al., 2025). Bias-correction values derived against GGG2020 are therefore not directly comparable with values derived against earlier releases. Re-deriving the corrections on the GGG2020.1 update changed the GOSAT offset by only 0.100 ppb, from 16.755 to 16.655 ppb, with the GOSAT-2 slope unchanged. The list of TCCON sites used and the number of co-located soundings at each site are given in Appendix D.

4.3 Co-location samples

Two co-location samples are used in this work. GOSAT is matched against TCCON for validation and for the GOSAT bias anchor, and GOSAT against GOSAT-2 for the GOSAT-2 cross-anchored bias correction and the inter-instrument comparison.

Satellite soundings are matched to TCCON measurements using the same spatial and temporal coincidence criteria as Parker et al. (2020). A sounding is co-located with a TCCON site if it falls within $\pm 5^\circ$ latitude and $\pm 5^\circ$ longitude of the site and within ± 2 hours of the TCCON measurement time. No additional screening is applied to the TCCON data beyond the network's own quality control. All soundings in the public files are used, averaged within the ± 2 hour window around the mean overpass time of each co-located day. These relatively broad spatial windows are necessary because of the sparse sampling of the GOSAT-type instruments. On any given day, few soundings fall close to a TCCON station, so a wider window is needed to accumulate sufficient statistics. The sounding density near a given station also reflects operational choice, since the targeted observations described in Sect. 2.2 are scheduled for individual sites rather than applied uniformly across the network. Similar or broader co-location windows are standard for GOSAT validation, ranging from a 500 km radius (Noël et al., 2022) to geographic boxes of $\pm 5^\circ$ latitude by $\pm 15^\circ$ longitude (Zhou et al., 2016) and dynamically defined regions spanning tens of degrees (Wunch et al., 2011b; Kulawik et al., 2016), and this choice is consistent with our previous work (Parker et al., 2011, 2015, 2020; Dils et al., 2014). Nguyen et al. (2014) discuss the underlying trade-off between co-location mismatch error and sampling statistics.

Figure 4 shows the spatial distribution of co-located GOSAT and GOSAT-2 soundings around three representative TCCON sites (Lamont, Tsukuba, and Harwell) during the instrument overlap period. The dashed box marks the $\pm 5^\circ$ coincidence window. The pattern illustrates a second benefit of the GOSAT-2 acquisition strategy. Because targeted observations can replace lattice points entirely, with the intelligent pointing then steering towards cloud-free land, the yield of land soundings increases particularly in coastal areas. GOSAT's own targeting was extended towards coastal and island sites during its mission (Sect. 2.2; Kuze et al., 2016), but the GOSAT-2 scheduling is more flexible. The effect is largest where land is scarce. Within $\pm 5^\circ$ of the island sites Tsukuba (Japan; Ohyama et al., 2009) and Harwell (UK; Weidmann et al., 2025), GOSAT-2 returns 13,079 and 8,092 quality-filtered land soundings over the overlap period against 7,785 and 5,469 for GOSAT, increases of 68 % and 48 %. At the inland Lamont site, where land fills the coincidence window for both instruments, the difference is far smaller (16,830 against 15,176, 11 %). This disproportionate gain reflects the improvements in the acquisition strategy for GOSAT-2 compared to GOSAT.



Examples of the GOSAT and GOSAT-2 Measurement Pattern Over TCCON Validation Sites

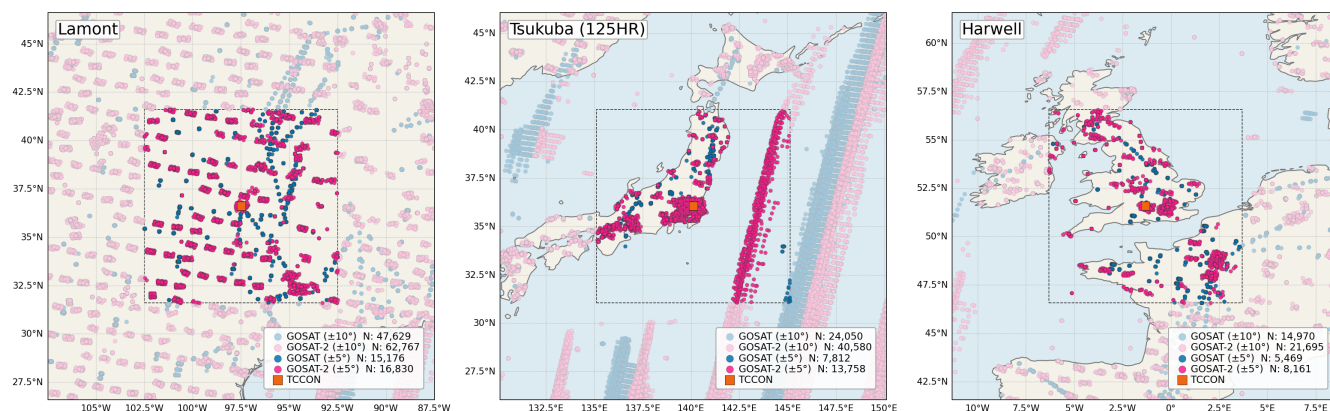


Figure 4. Spatial distribution of GOSAT (blue) and GOSAT-2 (magenta) soundings within the TCCON coincidence windows for three representative sites: Lamont (USA), Tsukuba (Japan), and Harwell (UK). Filled circles show soundings within $\pm 5^\circ$ (the matching window). Lighter points show the wider $\pm 10^\circ$ context. The dashed box marks the coincidence window boundary. The orange square marks the TCCON station location. Legend values (N) are the total quality-filtered soundings within the $\pm 5^\circ$ window over the 2019–2025 overlap period. The land-only counts quoted in Sect. 4.3 are equal or marginally smaller. At the coastal sites (Tsukuba, Harwell) GOSAT-2 returns substantially more quality-filtered land soundings within the coincidence window than the regularly gridded GOSAT (Sect. 4.3), reflecting the improved GOSAT-2 acquisition strategy.

355 For the cross-anchored bias correction (Sect. 5) and the inter-instrument comparison (Sect. 8) we additionally construct a GOSAT / GOSAT-2 matched-pair sample, pairs of individual soundings, one from each instrument, that observe the same air column at near-identical times. A GOSAT and a GOSAT-2 sounding form a matched pair if their footprint centres lie within 5 km and their observation times within 1 hour of one another and both pass quality filtering. Over the 2019–2025 overlap this yields 124,206 matched pairs. Because each pair samples the same column with the same retrieval algorithm, the inter-
 360 instrument difference isolates instrument-level effects without the dependence on separate TCCON co-location samples which may reflect inter-site biases. The two soundings of a pair may still view the column along different slant paths. This geometric difference is second order and is not expected to be systematic across the sample.

5 Bias correction

We apply an empirical bias correction to both Proxy retrievals against TCCON (Wunch et al., 2011a) to bring the satellite
 365 XCH₄ onto the WMO standard scale. The v10.0 GOSAT correction retains the form used in Parker et al. (2020), and GOSAT-2 v2.0 is then cross-anchored to GOSAT on the period of instrumental overlap. The two-stage construction is illustrated in Fig. 5.

The GOSAT correction is the network-mean satellite-minus-TCCON residual on the used-sites sample (25 sites, $N = 180,574$ co-locations) against the GGG2020.1 release of 19 June 2026 (the superscripts G1 and G2 denote GOSAT and

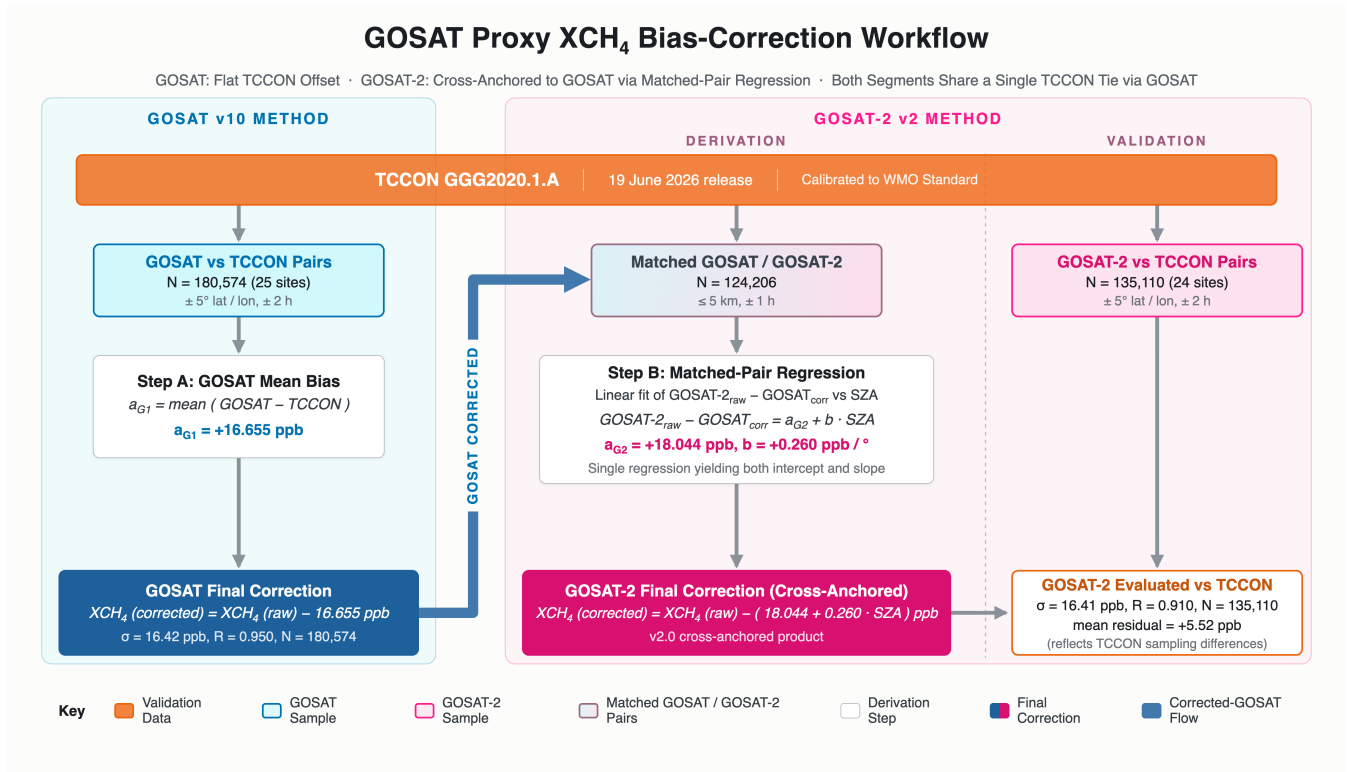


Figure 5. Workflow schematic of the v2.0 bias correction. GOSAT receives a single offset against TCCON (network-mean used-sites residual). GOSAT-2 is then cross-anchored to GOSAT over the 124,206 matched-pair footprints, with both the intercept ($a_{G2} = +18.044 \text{ ppb}$) and the SZA slope ($b_{\delta} = +0.260 \text{ ppb deg}^{-1}$) read off a single ordinary-least-squares fit through the bias-corrected matched-pair difference.

GOSAT-2 throughout):

$$XCH_4^{G1}_{\text{corr}} = XCH_4^{G1}_{\text{raw}} - 16.655 \text{ ppb.} \quad (2)$$

The form is unchanged from the v9.0 product (Parker et al., 2020) but the numerical value is updated for the GGG2020.1 TCCON release.

The GOSAT-2 correction has a linear dependence on the SZA at the sounding location (the solar illumination angle, distinct from the instrument viewing zenith angle) and is cross-anchored to GOSAT rather than fitted independently against TCCON, using the GOSAT / GOSAT-2 matched-pair sample defined in Sect. 4.3. Cross-anchoring is preferred because the matched-pair difference isolates instrument-level effects with none of the inter-site sampling dependency that affects each TCCON co-location sample separately. The raw matched-pair correlation in Fig. 6 (left) shows a clear positive offset between the two instruments. The right panel shows the post-correction matched-pair scatter sitting on the 1:1 line.

We use an ordinary-least-squares (OLS) fit of the bias-corrected matched-pair difference $\delta = XCH_4^{G2}_{\text{raw}} - XCH_4^{G1}_{\text{corr}}$ against SZA to obtain both the slope and the intercept of the GOSAT-2 correction (Fig. 7, left). Because δ is taken against the cor-



rected GOSAT values, its matched-pair mean of +27.50 ppb exceeds the raw-to-raw inter-instrument bias of +10.84 ppb (Fig. 6, left) by exactly the 16.655 ppb GOSAT offset. Both quantities describe the same 124,206 pairs. The fit returns $b_\delta = +0.260 \text{ ppb deg}^{-1}$ for the slope and $a_{G2} = +18.044 \text{ ppb}$ for the intercept, giving

$$\text{XCH}_4^{\text{G2}}_{\text{corr}} = \text{XCH}_4^{\text{G2}}_{\text{raw}} - (18.044 + 0.260 \cdot \text{SZA}) \text{ ppb}. \quad (3)$$

385 Because the OLS fit passes through the centroid of the matched-pair sample (the point defined by the mean SZA and the mean inter-instrument difference), the matched-pair mean and the residual SZA slope of the corrected difference $\delta_{\text{corr}} = \text{XCH}_4^{\text{G2}}_{\text{corr}} - \text{XCH}_4^{\text{G1}}_{\text{corr}}$ are both zero by construction (Fig. 7, right). Alternative functional forms ($\sec(\text{SZA})$, the Kasten–Young air mass of Kasten and Young 1989, and quadratic in SZA) were tested in the matched-pair fit but did not yield a statistically significant reduction in residual scatter, so the simplest two-parameter form is retained.

390 The physical origin of the GOSAT-2 SZA dependence is consistent with a residual sensitivity to the polarisation state of the incoming radiation. TANSO-FTS-2 measures two orthogonal polarisation components, and we reconstruct the scene radiance as their mean, which equals the true intensity only if the instrument response cancels the polarised components of the Stokes vector exactly. In practice this cancellation is imperfect, and the effective polarisation response of Band 2 varies with wavelength (cf. Fig. 4 of Suto et al. 2021), so the resulting radiance error differs between the spectral regions of the CH_4 and
 395 CO_2 fits. Such an error is radiometric rather than spectroscopic. Its magnitude scales with the degree of polarisation of the light reaching the instrument, which is set by the scattering geometry (largest near a scattering angle of 90°), the surface reflection, and aerosol, and it therefore varies systematically with SZA. The Proxy ratio cancels perturbations that affect the CH_4 and CO_2 retrievals in common mode, and the retrieved continuum absorbs any spectrally flat or slowly varying component, but a spectrally structured residual concentrated in one fit window projects preferentially onto the retrieved CH_4 and survives the
 400 ratio. The equivalent dependence in the GOSAT record is markedly weaker, which indicates that the corresponding polarisation residual for TANSO-FTS is smaller. A full radiative-transfer characterisation of this effect is beyond the scope of this work. The empirical correction of Eq. (3) removes its net effect at the dataset level, and SZA acts as an effective single-parameter description of the scattering geometry over the sounding ensemble.

A consequence of the cross-anchor is that the tie of the GOSAT-2 XCH_4 to the WMO scale runs through GOSAT rather than
 405 being established independently. The corrected GOSAT-2 therefore has a residual mean bias against TCCON of +5.52 ppb, evaluated on its used-sites sample (24 sites, $N = 135,110$) and inherited from the GOSAT TCCON tie through the cross-anchor. The trade-off is deliberate. Independent anchoring of each instrument to TCCON forces the mean residual to zero on each instrument separately but leaves a persistent $\sim 5 \text{ ppb}$ step in the combined record at the instrument boundary, arising from the geographic and temporal asymmetry of the two TCCON co-location samples. The cross-anchor removes this step by
 410 construction at the cost of a residual mean bias to TCCON, in the same spirit as the construction of multi-instrument climate records such as ERSST (Huang et al., 2017) and HadSST (Kennedy et al., 2019) for sea-surface temperature. It is important to highlight that this residual bias is retained by design and should not be read as an uncorrected instrument offset. Over the matched-pair sample the corrected instruments agree at the sub-ppb level. Because the mean satellite-minus-TCCON difference depends on the geographic and temporal distribution of each instrument’s co-location sample, forcing the GOSAT-2 mean to

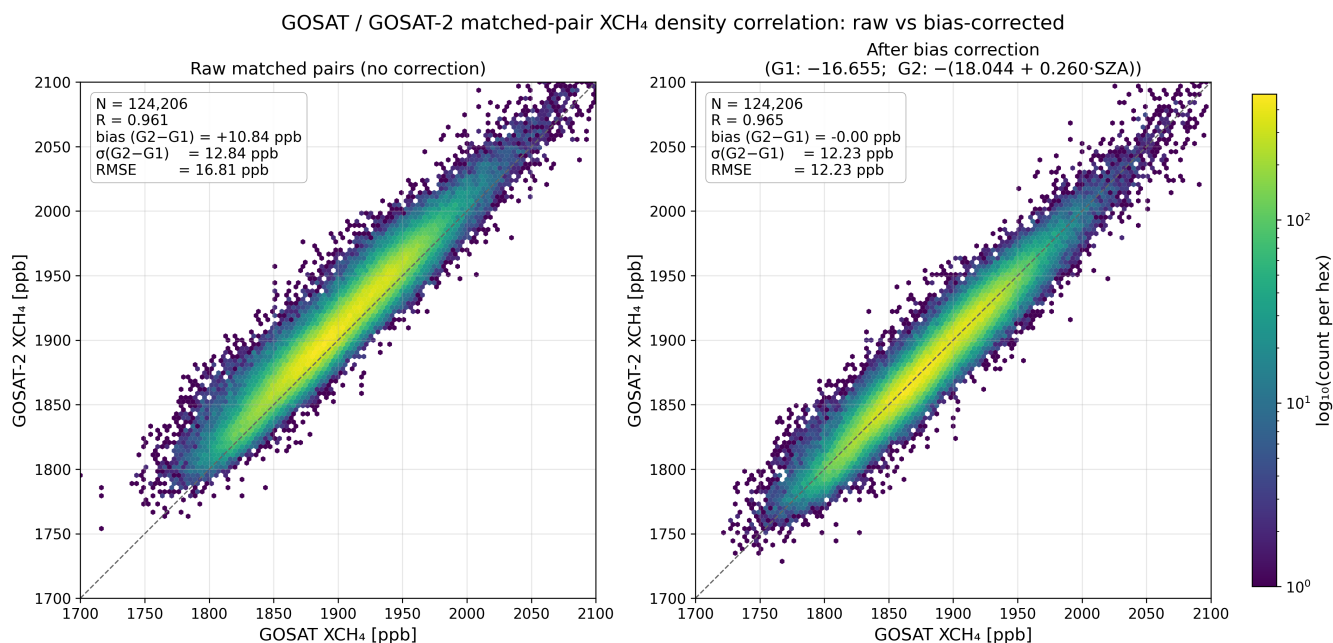


Figure 6. Density correlation of GOSAT and GOSAT-2 Proxy XCH₄ on the 124,206 co-located matched-pair footprints (≤ 5 km, ± 1 h, quality-filtered on both sides). Left: raw retrievals from both instruments. Right: after the v2.0 bias correction (a flat -16.655 ppb for GOSAT and the SZA-dependent $-(18.044 + 0.260 \cdot \text{SZA})$ ppb for GOSAT-2). Each panel shows a hexbin density on a logarithmic colour scale and the 1:1 line (dashed grey). The post-correction root-mean-square error drops from 16.81 to 12.23 ppb and the Pearson correlation rises from 0.961 to 0.965.

zero with a further constant adjustment would simply reintroduce the inter-instrument step that the cross-anchor is constructed to remove. Equivalently, a GOSAT-2 correction derived directly against TCCON would produce a dataset differing from the cross-anchored version by this same $+5.52$ ppb in the mean. The choice between the two anchoring strategies therefore determines only whether this offset appears as a mean bias to TCCON or as a step within the combined record. Figure 8 shows the satellite-minus-TCCON bias against SZA for both instruments, before (left) and after (right) the corrections defined in Eqs. (2) and (3). Before correction, the raw GOSAT-2 minus TCCON difference increases with SZA at $+0.380 \pm 0.003$ ppb deg^{-1} (Pearson $r = 0.34$), whereas the corresponding GOSAT dependence is markedly weaker ($+0.089 \pm 0.003$ ppb deg^{-1} , $r = 0.08$). After correction, the two instruments share a comparably small residual dependence on SZA against TCCON ($+0.09$ and $+0.12$ ppb deg^{-1} for GOSAT and GOSAT-2, respectively), the GOSAT-2 slope having been reduced by the cross-anchored correction to the level of the heritage instrument. The GOSAT-2 panel sits at the inherited $+5.52$ ppb offset, while GOSAT sits at zero by the construction of Eq. (2). The post-correction residual standard deviation of the satellite-minus-TCCON differences is $\sigma = 16.41$ ppb for GOSAT-2 and $\sigma = 16.42$ ppb for GOSAT. Per-site validation statistics are presented in Sect. 7.

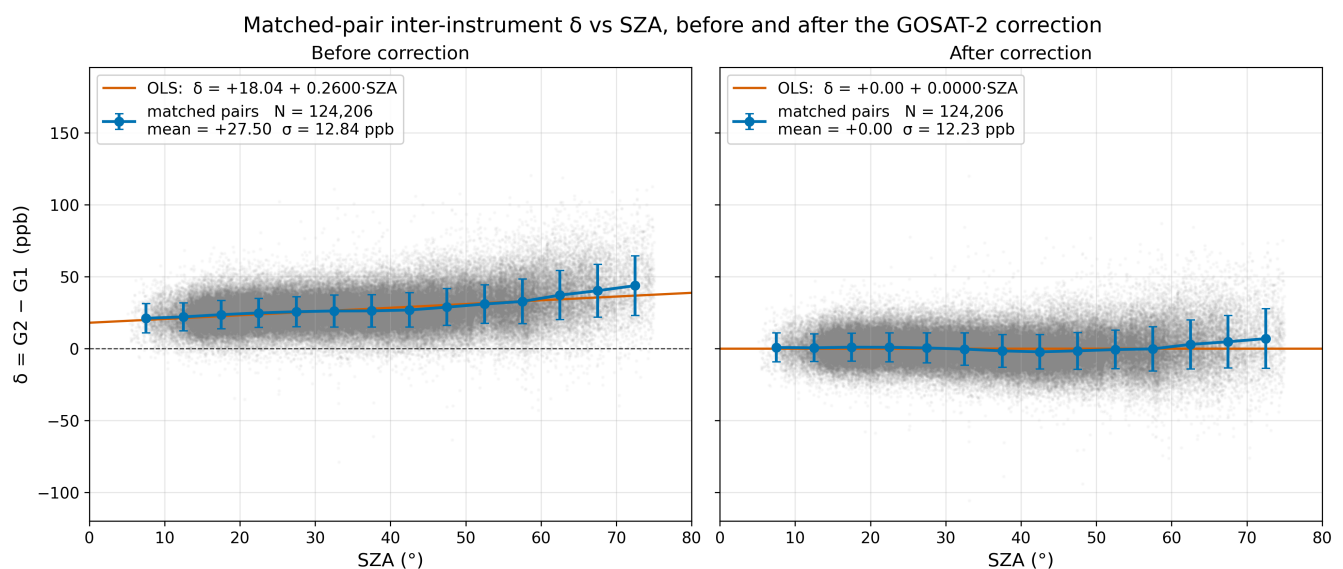


Figure 7. Matched-pair inter-instrument difference $\delta = G2 - G1$ as a function of solar zenith angle on the 124,206 GOSAT / GOSAT-2 co-located footprints, before and after the GOSAT-2 correction. Left panel: $\delta = G2_{\text{raw}} - G1_{\text{corr}}$, the quantity fitted in Sect. 5. The ordinary-least-squares fit has intercept $a_{G2} = +18.044$ ppb and slope $b_{\delta} = +0.260$ ppb deg^{-1} . Right panel: $\delta = G2_{\text{corr}} - G1_{\text{corr}}$, after the GOSAT-2 correction. The residual intercept and slope are both zero on the matched-pair sample by construction of the cross-anchor. Grey points are individual matched pairs. Blue markers with error bars are 5° SZA-binned means $\pm 1\sigma$. The orange line is the OLS fit reported in the panel legend.

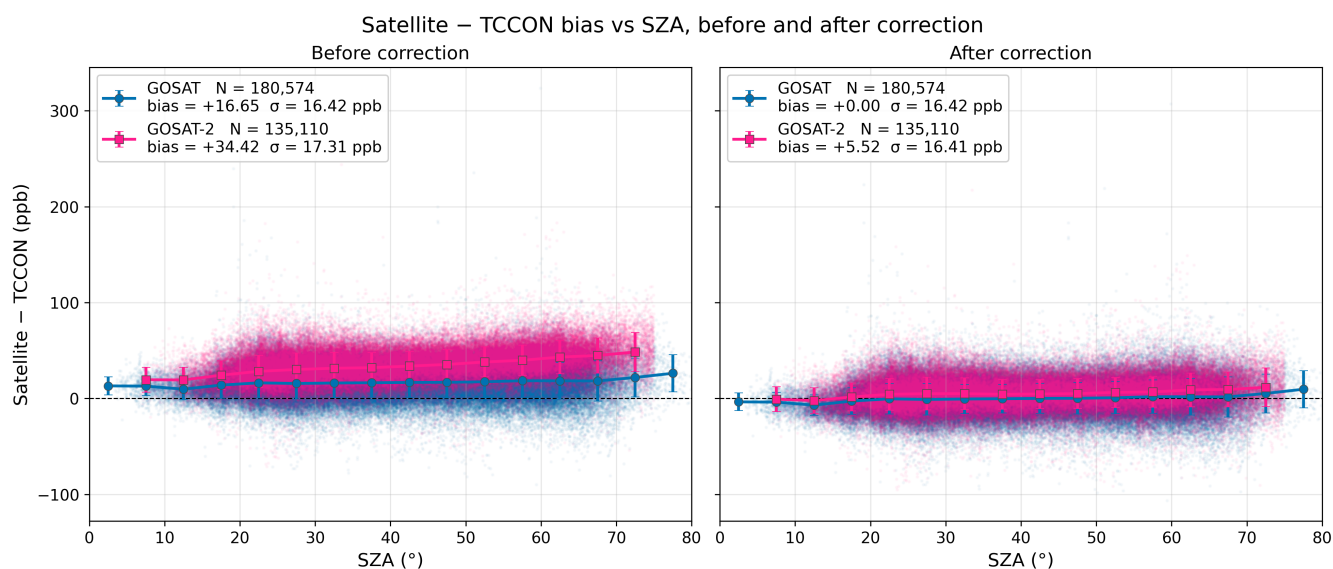


Figure 8. Satellite minus TCCON Proxy XCH_4 bias as a function of solar zenith angle for both instruments on the used-sites sample (GOSAT: 25 sites, $N = 180,574$; GOSAT-2: 24 sites, $N = 135,110$), before (left) and after (right) the v2.0 bias correction. GOSAT in blue, GOSAT-2 in magenta. Points are individual matched pairs. Markers with error bars are 5° SZA-binned means $\pm 1\sigma$. After correction, the GOSAT panel sits at zero by the construction of Eq. (2). The GOSAT-2 panel sits at the inherited +5.52 ppb network-mean offset described in Sect. 5. The legend in each panel reports the per-instrument mean residual and standard deviation.



6 Dataset characterisation

6.1 Temporal coverage

Figure 9 shows the monthly count of quality-filtered GOSAT-2 Proxy XCH₄ retrievals for the period 2019–2025, split into all
430 retrievals, land (nadir) only, and ocean (glint) only. The seasonal pattern is driven by solar illumination. High-latitude retrievals
are available only during their respective spring and summer months, while tropical coverage is more uniform but reduced
by cloud contamination. Several months show reduced counts caused by the orbit-control campaigns and protective standby
transitions described in Sect. 2.3.

6.2 Global XCH₄ distribution

435 Figure 10 presents the seasonal mean GOSAT-2 Proxy XCH₄ on a 2° grid for each year of the record (2019–2025), aggregated
into the standard meteorological seasons (MAM, JJA, SON, DJF). The spatial distribution reflects the well-known features
of the global methane field. XCH₄ is highest in the Northern Hemisphere, with the seasonal maximum in boreal autumn.
Over 30–60° N the monthly climatology peaks in October–December, approximately 25 ppb above its late-spring minimum,
as emissions accumulate in the column while the OH sink declines from its summer peak. The inter-hemispheric gradient is
440 visible in all seasons, with Southern Hemisphere values 50–80 ppb lower than those in the Northern Hemisphere mid-latitudes.
Within the tropics, elevated XCH₄ is apparent over South and Southeast Asia, central Africa, and the Amazon basin, consistent
with known wetland and agricultural methane source regions.

Year-to-year changes are also visible. The global background level increases across the record, consistent with the continued
growth in atmospheric methane concentrations reported by surface flask networks, which averages approximately 11 ppb yr⁻¹
445 (∼0.6 % yr⁻¹) over 2019–2025 (Lan et al., 2022).

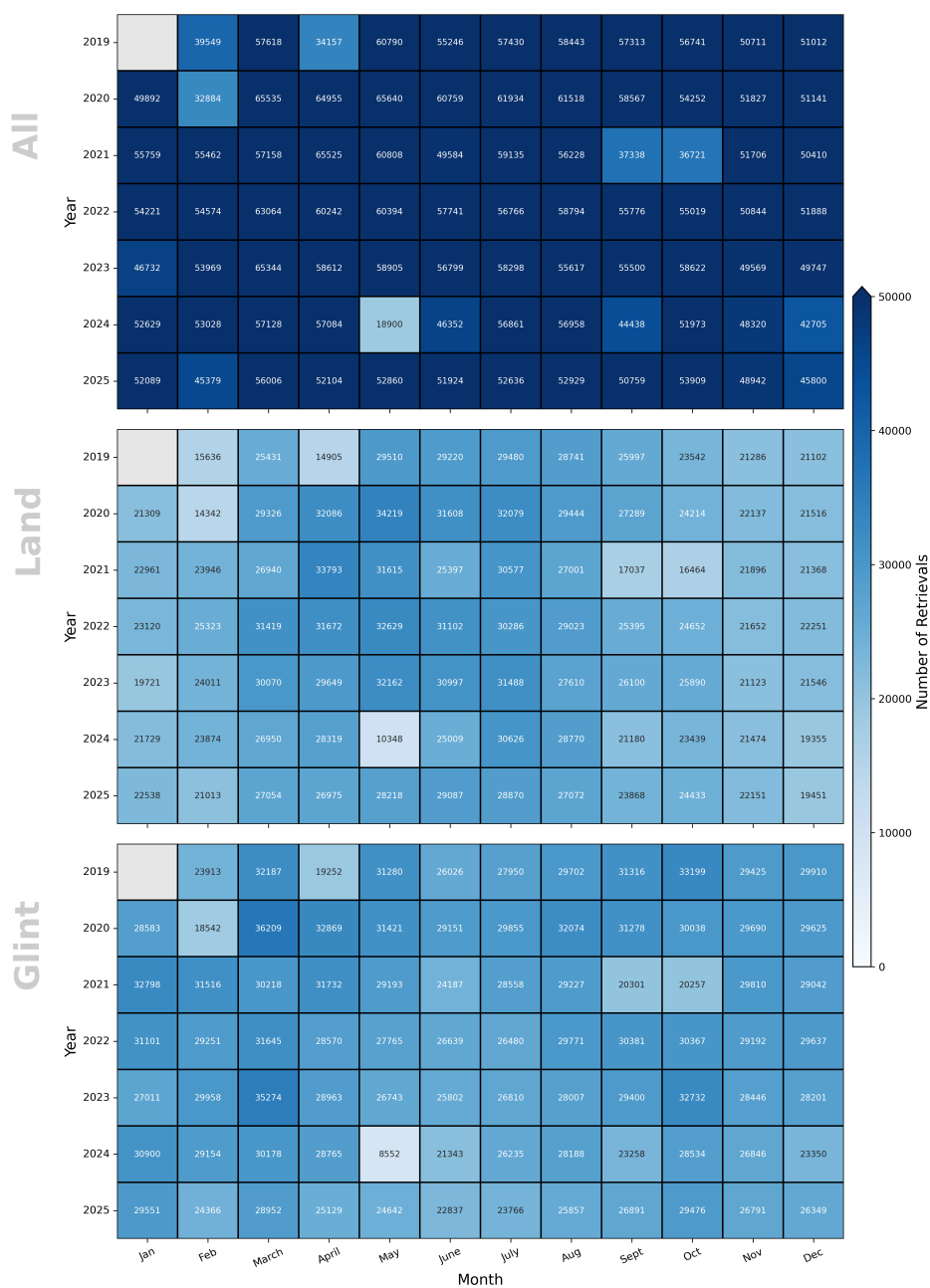


Figure 9. Monthly retrieval counts for quality-filtered GOSAT-2 Proxy XCH₄ over 2019–2025. The three panels show all retrievals (top), land nadir retrievals (middle), and ocean glint retrievals (bottom). Cell colour indicates the number of quality-filtered soundings per month.

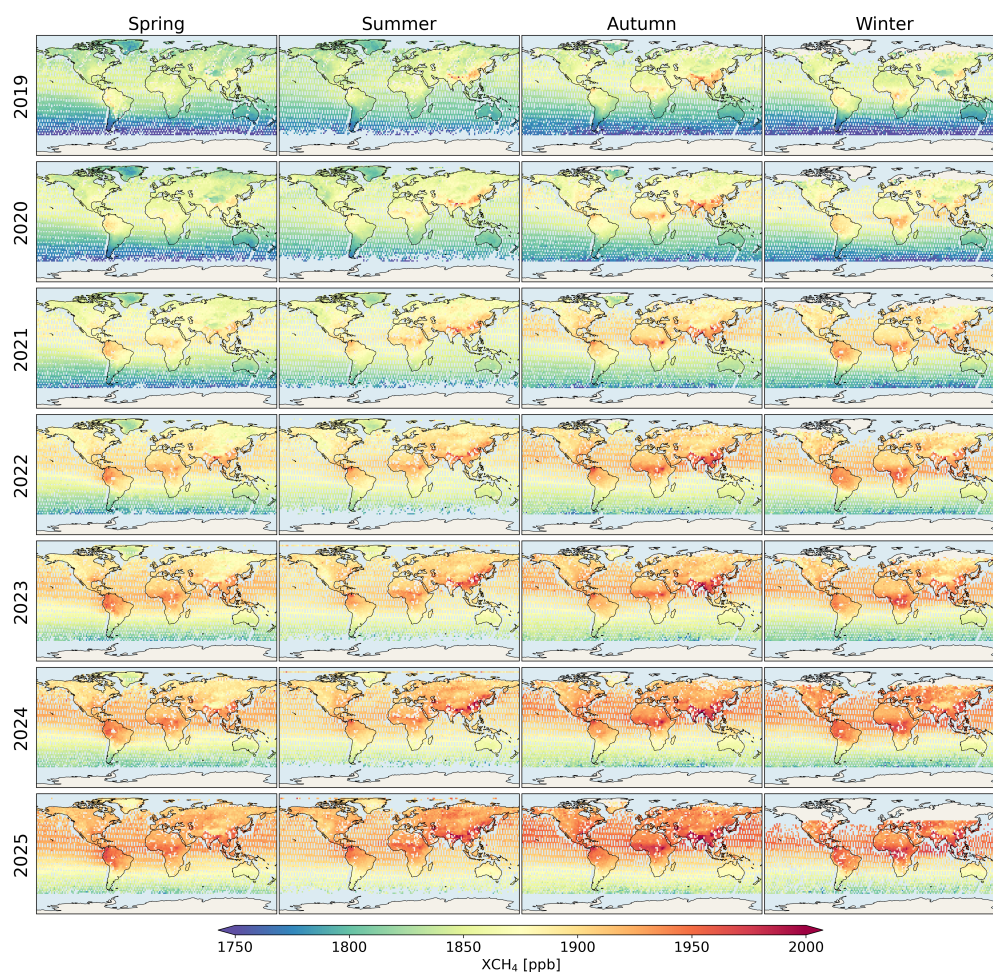


Figure 10. Seasonal mean GOSAT-2 Proxy XCH₄ on a 2° grid for 2019–2025. Columns show MAM, JJA, SON, and DJF. Rows show individual years. The Northern Hemisphere enhancement is clearly visible, largest in the SON panels, as is the year-on-year growth in the global background.



7 Validation against TCCON

We validate both Proxy XCH₄ products against ground-based TCCON measurements, using the network described in Sect. 4.2 and the GOSAT–TCCON co-location criteria defined in Sect. 4.3. We first report the global validation statistics for GOSAT-2 and, for context, for GOSAT over its full record, then examine the combined per-site performance.

450 7.1 GOSAT-2 validation

Figure 11 (right column) shows the density of co-located GOSAT-2 and TCCON XCH₄ over the full GOSAT-2 record, before (top) and after (bottom) the v2.0 bias correction. The overall statistics (global mean bias, standard deviation of the differences representing single-sounding precision, and Pearson correlation coefficient) are annotated on each panel.

After applying the v2.0 bias correction defined in Sect. 5, the standard deviation of the GOSAT-2 minus TCCON differences
 455 is 16.41 ppb, providing an estimate of the single-sounding random error. The Pearson correlation coefficient is 0.910 across $N = 135,110$ co-locations spanning 24 validation sites. The residual mean bias against TCCON is +5.52 ppb rather than zero, a consequence of anchoring the GOSAT-2 correction to GOSAT rather than directly to TCCON (Sect. 5). The SZA-dependent component of the bias is successfully removed by the bias correction, as shown in Fig. 8, despite the correction being derived from the GOSAT / GOSAT-2 matched pairs with no use of the GOSAT-2 TCCON co-locations.

460 7.2 GOSAT validation

To provide context for the GOSAT-2 performance and to assess the consistency of the combined data record, we apply the same validation procedure to the GOSAT Proxy XCH₄ v10.0 dataset (Parker et al., 2020, 2026b) over its full record (April 2009 onward). Figure 11 (left column) shows the equivalent comparison for GOSAT. After applying the GOSAT bias correction of 16.655 ppb, the standard deviation of the satellite-minus-TCCON differences is 16.42 ppb and the Pearson correlation is 0.950
 465 across $N = 180,574$ co-locations from 25 sites. The GOSAT validation statistics are consistent with those of GOSAT-2, which is expected given that the two datasets use the same retrieval algorithm, a priori fields, and quality filtering approach. Minor differences in bias or scatter between the instruments can arise from differences in SNR, spectral calibration, or the spatial sampling of the two satellites.

Taken together, the global TCCON validation statistics, standard deviations of 16.42 ppb (GOSAT) and 16.41 ppb (GOSAT-
 470 2) and correlations of 0.950 and 0.910 respectively, across more than 300,000 co-locations from 24–25 sites, demonstrate that the Proxy retrieval reproduces ground-based XCH₄ consistently for both instruments, and that the GOSAT-2 dataset achieves the same level of precision as the established GOSAT product. The per-site distribution of these statistics is examined in Sect. 7.4.

7.3 Combined GOSAT and GOSAT-2 timeseries

475 Figure 12 presents per-site monthly median XCH₄ timeseries with GOSAT, GOSAT-2, and TCCON overlaid on the same panel for each site. This combined view illustrates the continuity of the satellite record relative to the ground-based reference. At

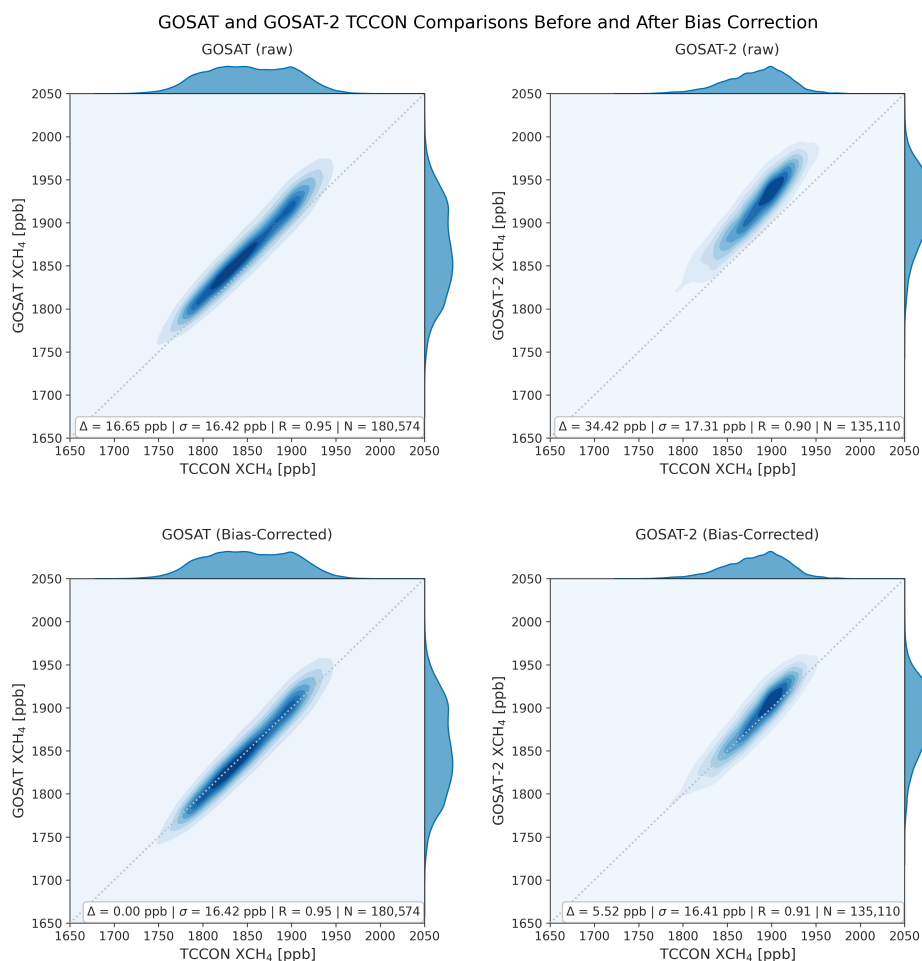


Figure 11. Two-dimensional kernel-density estimates of Proxy XCH₄ against co-located TCCON XCH₄, arranged as a 2×2 panel grid with marginal distributions shown on each axis. Left column: GOSAT over its full record (2009–2025). Right column: GOSAT-2 over its full record (2019–2025). Top row: raw retrievals. Bottom row: after the v2.0 bias correction (Sect. 5). The dashed line is the 1:1 reference. Global bias (Δ), standard deviation (σ), Pearson correlation (R), and number of co-locations (N) are annotated in each panel.

sites where both instruments have data during the overlap period, the GOSAT and GOSAT-2 timeseries track each other closely, with both following the TCCON seasonal cycle and long-term trend.

The per-site bias and correlation for each instrument are annotated on each panel. Some sites show small but consistent offsets between the two satellite instruments, discussed further in the context of the inter-instrument comparison in Sect. 8.

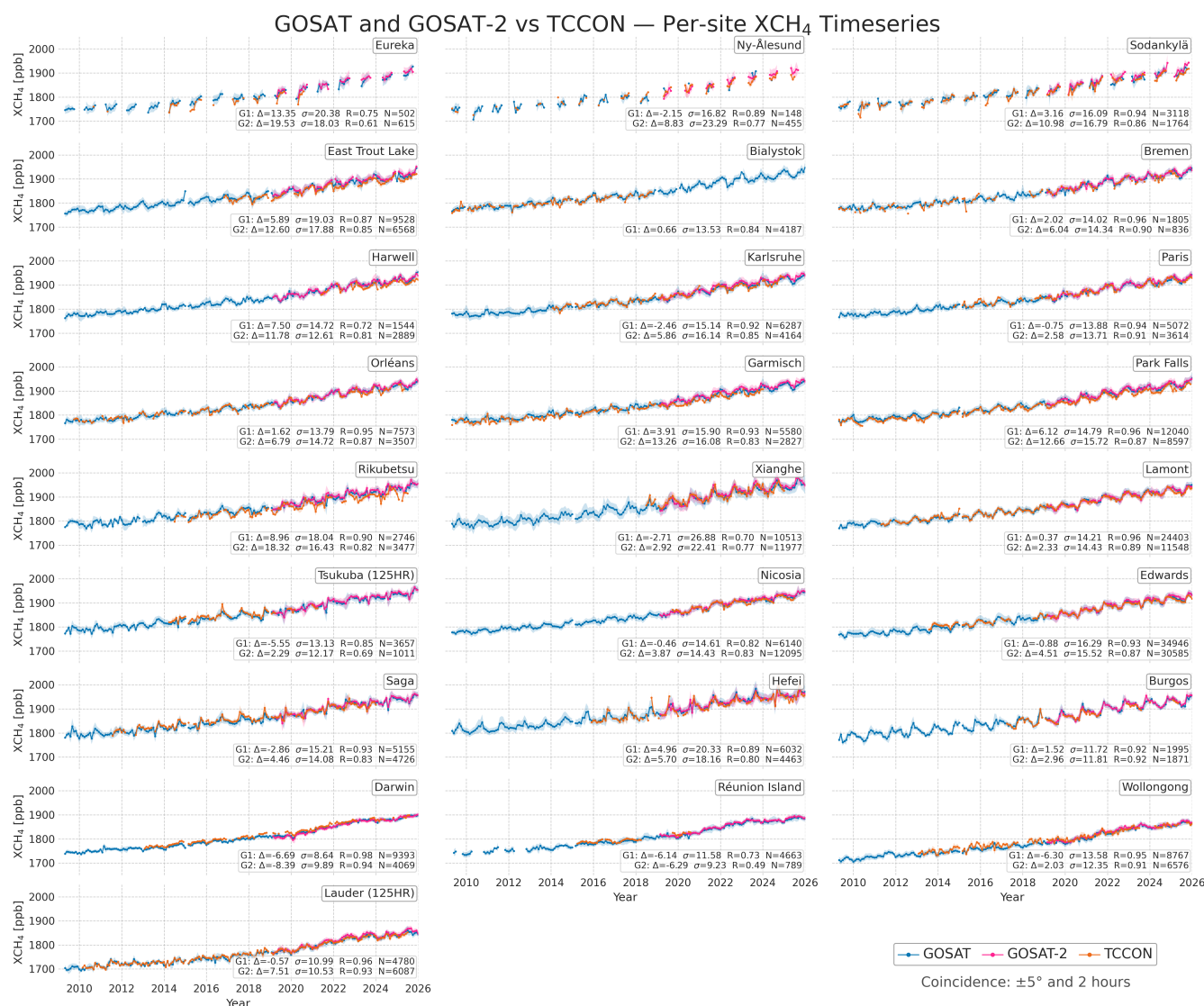


Figure 12. Per-site monthly median XCH₄ timeseries for GOSAT (blue), GOSAT-2 (magenta), and TCCON (orange). Each panel shows one TCCON site, ordered north-to-south. Site coordinates and details are given in Table D1 (Appendix D). All sites used in the validation are shown; the Bialystok record ends in October 2018, before the start of GOSAT-2 observations, so its panel shows GOSAT and TCCON only. Shaded bands show the $\pm 1\sigma$ envelope of the monthly medians. The GOSAT and GOSAT-2 lines are computed from all soundings within the co-location box, whereas the TCCON line shows only days co-located with at least one satellite instrument. Per-instrument bias (Δ), standard deviation (σ), correlation (R), and sample size (N), computed from strictly co-located soundings, are annotated.



7.4 Per-site validation statistics

Figure 13 summarises the per-site validation statistics, bias, standard deviation, Pearson correlation, and number of co-locations, for GOSAT (full record), GOSAT restricted to the GOSAT-2 overlap period (2019–2025), and GOSAT-2. Sites are ordered north-to-south. The three datasets show broadly consistent per-site performance. The GOSAT correction is a single flat offset (Sect. 5), so the per-site GOSAT residuals scatter around zero. The GOSAT-2 correction is SZA-dependent and cross-anchored to GOSAT, so the per-site GOSAT-2 residuals scatter around +5.52 ppb, the network-mean offset inherited from GOSAT's TCCON tie (by construction rather than a per-site artefact). Per-site standard deviations cluster around the network-mean values (16.42 ppb for GOSAT and 16.41 ppb for GOSAT-2), with the largest values at high-latitude sites (Eureka, Batchelor et al., 2009; Ny-Ålesund; Sodankylä, Kivi and Heikkinen, 2016; East Trout Lake), where large solar zenith angles and low signal levels limit retrieval precision, and at Xianghe and Hefei, consistent with strong regional emission gradients within the co-location radius. The smallest scatter occurs at the Southern Hemisphere sites (Darwin, Réunion, Lauder), consistently below 12 ppb. Per-site Pearson correlations exceed 0.7 at the majority of sites, reaching above 0.9 at the well-sampled mid-latitude stations. The overlap-period GOSAT statistics fall between the full-record GOSAT and GOSAT-2 values at most sites, indicating that temporal sampling rather than instrument differences drives most of the inter-dataset variability.

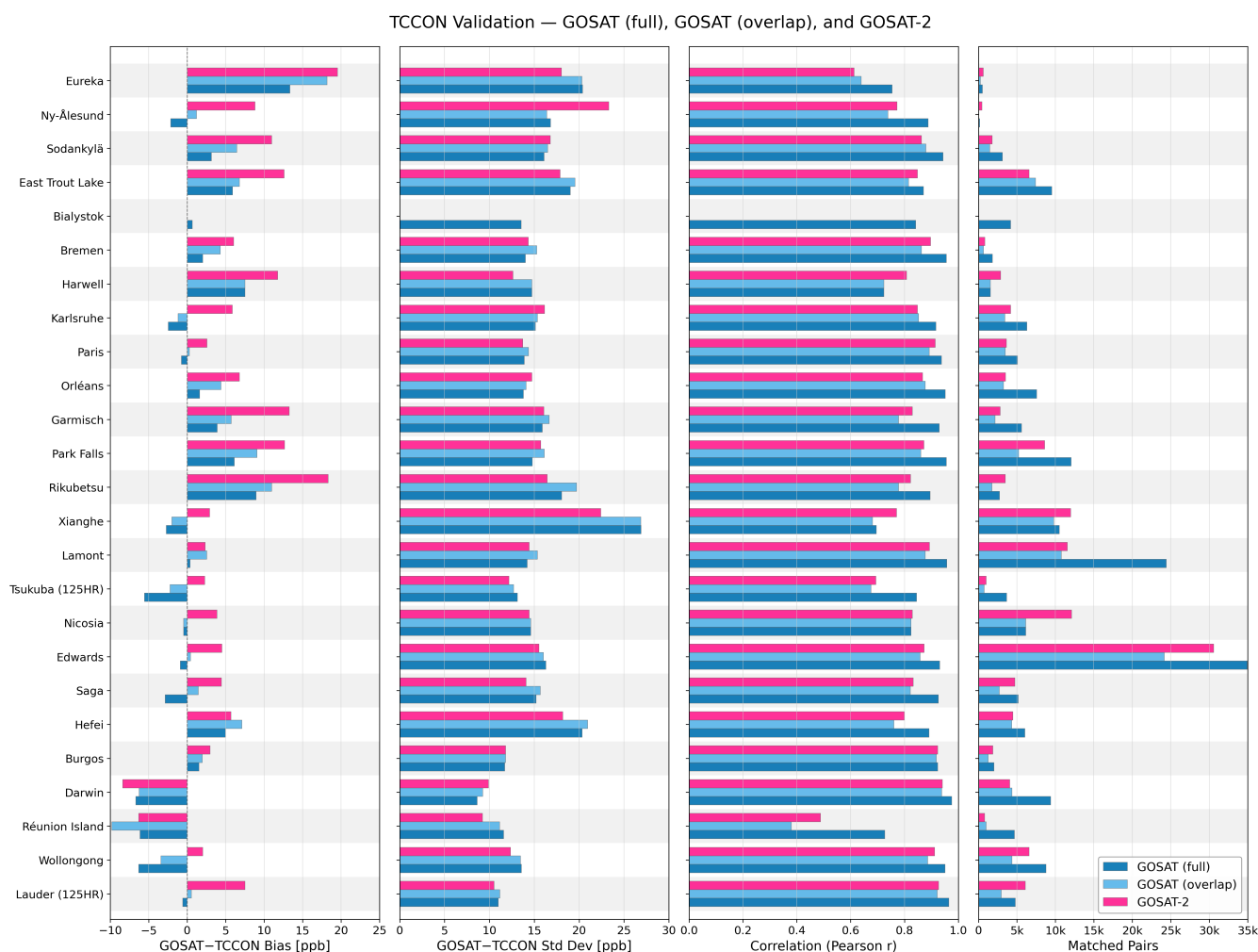


Figure 13. Per-site TCCON validation statistics for GOSAT (full record, blue), GOSAT restricted to the GOSAT-2 overlap period 2019–2025 (sky blue), and GOSAT-2 (magenta). From left to right: bias relative to TCCON (ppb), standard deviation of the differences (ppb), Pearson correlation coefficient, and number of co-located pairs. Sites are ordered north-to-south. Site details are given in Table D1.



495 8 Towards a combined GOSAT and GOSAT-2 climate data record

GOSAT has been an extremely successful mission, far exceeding its planned 5-year mission lifetime. As would be expected, it has suffered various instrumental anomalies as it ages (see Parker et al., 2020) and is now reliant on several redundancy systems. At some stage, GOSAT will fail, so ensuring that GOSAT-2, and in time GOSAT-GW (Miura et al., 2023; Tanimoto et al., 2025), can continue the GOSAT legacy is vital, maintaining this important long-term climate data record. A primary
 500 objective of our GOSAT-2 Proxy XCH₄ retrieval is to produce a dataset that is consistent with the existing GOSAT Proxy record, so the two can be combined into a single climate data record spanning 2009 to present, extending into the future. Both datasets are produced using the same Proxy retrieval algorithm, the same model priors, and the same quality filtering framework, minimising methodological differences between the two records.

Figure 14 shows the full latitude–time evolution of monthly XCH₄ for both instruments. The GOSAT record extends from
 505 2009 and GOSAT-2 from 2019. The two panels share a common colour scale so that any systematic offset would appear as a visible step change at the instrument transition. No such discontinuity is apparent, providing an immediate qualitative confirmation of record consistency. A conspicuous feature of both panels is the pale band of near-constant XCH₄ that migrates southward across the record. This is the 1850 ppb isopleth, the midpoint of the colour scale. As the growing global background rises through this level, the latitude at which the zonal mean equals 1850 ppb sweeps from approximately 13° N in 2017 to
 510 approximately 45° S by 2025. Its descent is fastest, approximately 13° of latitude per year, during 2020–2022, when record growth rates driven predominantly by tropical wetland emissions raised the low-latitude background most rapidly (Peng et al., 2022; Feng et al., 2023; Qu et al., 2024). Because values along the slowly migrating isopleth remain close to 1850 ppb, it appears as a line of suppressed seasonal variability. Both instruments place the isopleth at the same latitude to within approximately 2° in every year of the overlap, a further measure of the consistency of the combined record.

515 The inset in Fig. 14 provides the quantitative continuity check. The monthly global-mean Proxy XCH₄ from both instruments is shown across the full record, with $\pm 1\sigma$ within-month shading. Across the 83 months of temporal overlap (2019–2025), the inter-instrument monthly-mean residual is $\langle G2 - G1 \rangle = +1.33$ ppb with a month-to-month standard deviation of 3.29 ppb. The small positive residual is the expected consequence of the cross-anchored correction defined in Sect. 5. The correction forces the matched-pair mean difference to zero, but the matched-pair sample weights latitudes differently from either instrument's
 520 full sampling. Over half of the pairs lie within 30° of the equator, where the matched difference is negative, while the northern extratropical bands carry positive differences (Appendix H), so the full-sampling global mean is not constrained to zero. Recomputing the monthly global means with both instruments restricted to the 2° grid cells they sample in common reduces the month-to-month standard deviation of the difference from 3.29 to 1.13 ppb and removes its apparent seasonal oscillation. The visible variability between the two curves in the inset therefore reflects the differing spatial coverage of the two instruments
 525 rather than instrument behaviour. A stricter demonstration using only footprint-matched soundings, together with guidance on comparing the two records, is given in Appendix H. The absence of any visible step at the GOSAT-2 record start (2019) confirms that the combined GOSAT + GOSAT-2 record can be used as a single continuous time series for trend and seasonal-cycle analysis.

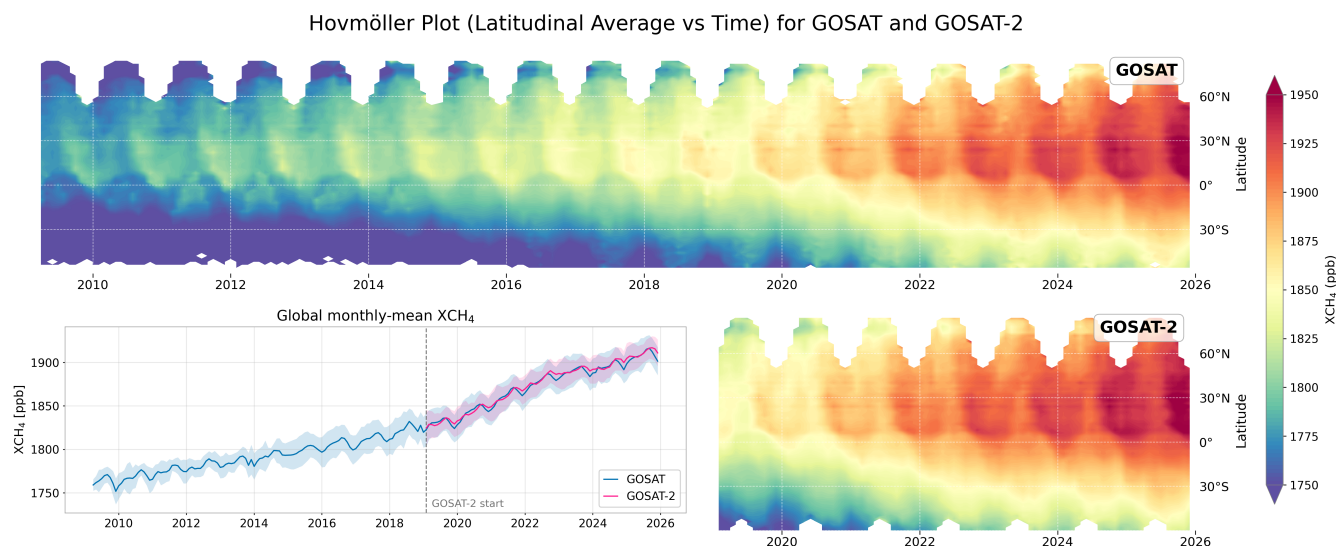


Figure 14. Latitude–time Hovmöller diagrams of monthly mean Proxy XCH_4 from (a) GOSAT and (b) GOSAT-2. The colour scale is identical for both panels. The GOSAT record begins in 2009 and the GOSAT-2 record begins in early 2019. The inset shows the monthly global-mean Proxy XCH_4 from GOSAT (blue, 2009–2025) and GOSAT-2 (magenta, 2019–2025) with $\pm 1\sigma$ within-month shading. The dashed vertical line marks the GOSAT-2 record start. Across the 83 months of overlap, the inter-instrument monthly-mean residual is $\langle G2 - G1 \rangle = +1.33$ ppb with 3.29 ppb of month-to-month scatter.

8.1 Regional time series

Figures 15 and 16 show monthly mean XCH_4 for GOSAT and GOSAT-2 across the 16 TransCom land regions and 11 TransCom ocean regions (Gurney et al., 2002), respectively, using the full available record of each instrument (GOSAT: 2009–2025; GOSAT-2: 2019–2025).

During the overlap period, the two instruments track each other closely in all regions, with small and generally stable biases. Over land, the mean GOSAT-2 minus GOSAT bias is typically within ± 5 ppb across regions. The shaded envelopes ($\pm 1\sigma$) indicate the within-region variability, which is comparable for both instruments, confirming that GOSAT-2 captures the same spatial heterogeneity as GOSAT. Over the bright-surface desert interior of Temperate Northern Africa we do see potential small differences between the two records during the winter months, which persist for footprint-matched soundings. These may be related to scene-dependent effects for bright or dust-laden surfaces viewed at high solar zenith angle, or to the more complex gain configuration of TANSO-FTS-2 (Sect. 3.3), and merit further investigation.

It should be noted here that the detector assembly of TANSO-FTS-2 differs from that of TANSO-FTS. We have seen early evidence, in the form of poorer spectral fits in Band 1, that the GOSAT-2 detectors may have a higher sensitivity to the South Atlantic Anomaly (SAA) than those of GOSAT, and for that reason data in that region may fail stringent quality checks. However, this effect appears largely confined to Band 1, so while it may impact a multi-band Full-Physics retrieval, it has



Figure 15. Monthly mean Proxy XCH₄ for GOSAT (blue) and GOSAT-2 (magenta) in each of the 16 TransCom land regions, using the full record of each instrument. Shaded regions show $\pm 1\sigma$. Annotation in each panel shows the number of soundings per instrument and the mean bias (GOSAT-2 minus GOSAT) during the overlap period.

minimal effect on our Band 2 Proxy retrieval. We have tested this and although GOSAT-2 traverses the SAA, its imprint on the retrievals over the South American Temperate region is limited to a small relative enhancement of the spectral-fit χ^2 (approximately +4 % for the CH₄ band against the all-land median), with no reduction in quality-filtered yield. The apparent divergences between the two records in this panel are a sampling effect. The 3,705 matched soundings (Sect. 4.3) within the region agree to $+0.2 \pm 0.2$ ppb with a per-sounding correlation of $r = 0.97$, matching the full matched-pair sample, and we therefore find no evidence of an SAA-induced bias in the Proxy XCH₄.

Over ocean regions, the agreement is similarly close, with consistent seasonal cycles between the two instruments. Soundings are assigned to regions by location, so the ocean regions are sampled predominantly, although not exclusively, by glint-mode observations. Some high-latitude ocean regions (e.g. Southern Ocean) have sparse GOSAT coverage in certain years (prior to the extension of the glint-mode observation to cover a wider latitude range), reflected in gaps in the time series.

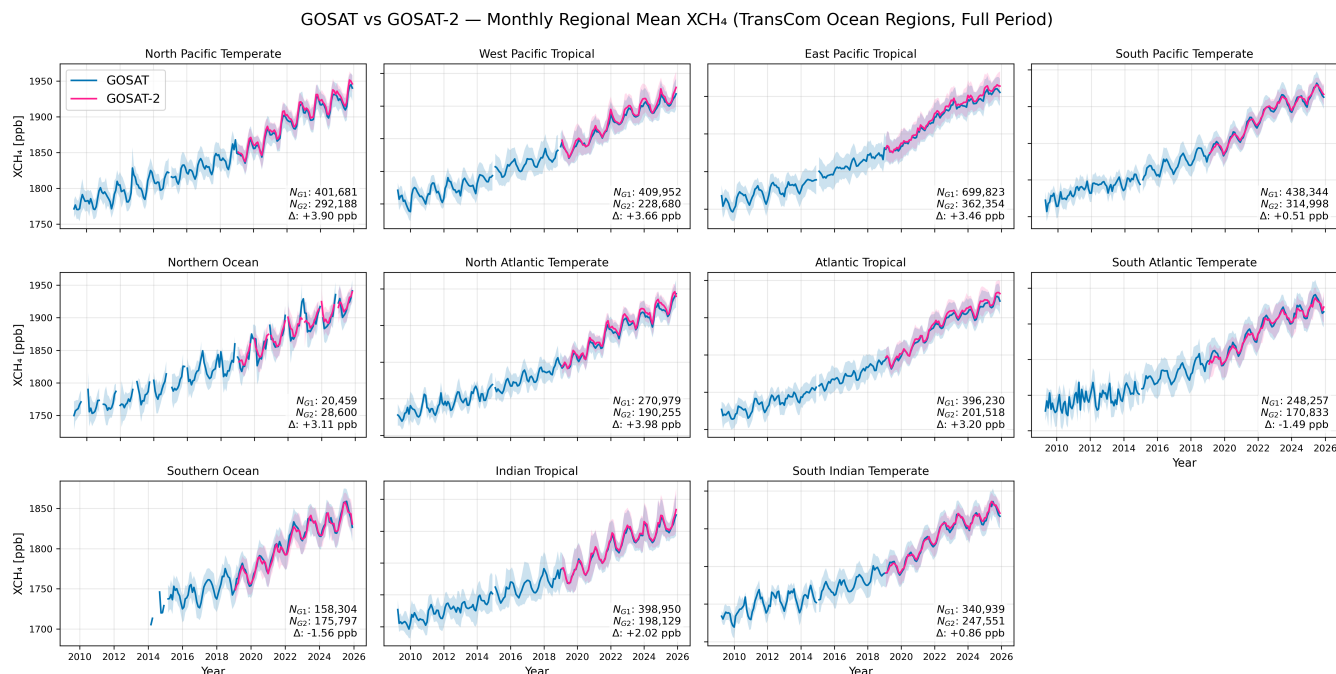


Figure 16. As Fig. 15 but for the 11 TransCom ocean regions.

8.2 Correlation and bias

555 To quantify the agreement between the two datasets more rigorously, we compute co-located monthly means on a common 2° grid during the overlap period and compare them as scatter plots. Figure 17 shows this comparison for all scenes combined (left), land retrievals only (centre), and glint retrievals only (right).

The correlation is high in all three samples ($r = 0.96$ overall, 0.95 for land and 0.97 for glint), with a mean bias (GOSAT-2 minus GOSAT) of +2.3 ppb (+1.9 ppb for land, +3.0 ppb for glint) and an RMSE of 10.6–12.5 ppb. The regression slopes lie
 560 between 0.95 and 0.99. The land-only and glint-only panels show similar statistics, and the small land-glint difference in mean bias is comparable to the month-to-month variability of the matched inter-instrument difference (Appendix H) and far below the single-sounding scatter, so no separate scene-type correction is warranted.

These results demonstrate that the GOSAT-2 Proxy XCH₄ dataset can be combined with the GOSAT record to form a continuous climate data record, with no adjustment beyond the cross-anchored bias correction and no separate treatment of the
 565 land and glint observation modes required.

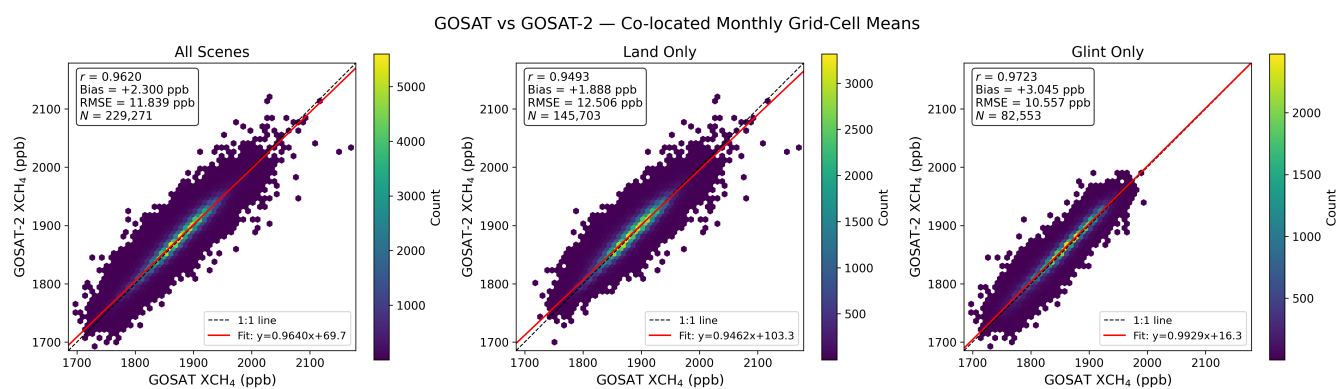


Figure 17. Scatter plots of co-located monthly 2° grid-cell mean Proxy XCH_4 from GOSAT (x-axis) and GOSAT-2 (y-axis) during the overlap period (2019–2025). Left: all scenes. Centre: land retrievals only. Right: glint retrievals only. Colour indicates the density of points. The dashed black line is the 1:1 line. The solid red line is the linear regression fit. Statistics (Pearson r , mean bias, RMSE, and number of co-located grid cells) are annotated in each panel.



9 Summary and outlook

We have presented version 2.0 of the UoL Proxy XCH₄ GOSAT-2 retrieval, covering February 2019 to December 2025 and comprising approximately 4.4 million quality-filtered column-averaged dry-air methane retrievals in both land nadir and ocean glint observation modes. The central result is that GOSAT-2, processed with the same algorithm, a priori fields, and quality filtering as the GOSAT Proxy v10.0 product (Parker et al., 2020, 2026b) and tied to it through a cross-anchored bias correction, extends the University of Leicester GOSAT Proxy record into a single, internally consistent satellite XCH₄ climate data record spanning 2009 to 2025. This 17-year record covers the period of renewed and accelerating growth in atmospheric methane.

GOSAT-2 reaches the precision of the heritage instrument. After bias correction (a flat -16.655 ppb for GOSAT and an SZA-dependent $-(18.044 + 0.260 \cdot \text{SZA})$ ppb for GOSAT-2; Sect. 5), the standard deviation of the satellite-minus-TCCON differences is 16.41 ppb for GOSAT-2 against 16.42 ppb for GOSAT, with Pearson correlations of 0.910 and 0.950 respectively across more than 300,000 co-locations. The GOSAT-2 correction is cross-anchored to GOSAT rather than fitted independently to TCCON, leaving the corrected GOSAT-2 with a residual mean TCCON bias of $+5.52$ ppb in exchange for inter-instrument consistency over the overlap. Per-site GOSAT residuals scatter around zero and GOSAT-2 residuals around this offset (Sect. 7.4).

That consistency is confirmed directly. Over the 2019–2025 overlap, co-located monthly 2° grid-cell means from the two instruments correlate at $r = 0.95\text{--}0.97$, with a mean bias of $+2$ to $+3$ ppb and regression slopes of $0.95\text{--}0.99$ for land nadir and ocean glint scenes alike, so beyond the cross-anchored correction no further adjustment for either observation mode is required, and the two records join without a step at the instrument transition. The combined record reproduces the expected large-scale structure of the global methane field, the Northern Hemisphere autumn seasonal maximum, the inter-hemispheric gradient, and the elevated columns over the major tropical source regions, together with the sustained year-on-year rise in the global background.

A distinguishing feature of GOSAT-2 is its intelligent pointing system and improved acquisition mode. In under seven years it has returned about half as many soundings as GOSAT accumulated over more than sixteen, and by steering observations towards cloud-free land scenes it raises the yield of usable land retrievals at coastal and island sites (Sect. 3.5 and Sect. 4.3).

There are several limitations to note. The Proxy retrieval method depends on an independent model estimate of XCO₂, and any systematic errors in the model transport or surface fluxes will propagate into the retrieved XCH₄ at a level of approximately 0.5 % (Parker et al., 2020). GOSAT-2 has a 6-day repeat cycle and a 9.6 km nadir footprint, which, as for GOSAT, limits spatial sampling. The dataset is therefore best suited to monthly or seasonal aggregations rather than synoptic-scale analysis. Cloud contamination reduces coverage at low and mid-latitudes, particularly in the boreal summer monsoon season.

Looking ahead, the GOSAT-2 record is expected to continue growing, progressively extending the combined GOSAT + GOSAT-2 climate data record. The launch of GOSAT-GW in June 2025 (Miura et al., 2023; Tanimoto et al., 2025) offers the prospect of extending this record further, and applying the same Proxy retrieval approach to its observations is a priority for future work. The consistent retrieval algorithm applied to GOSAT and GOSAT-2, combined with the overlap period demonstrated here, provides a firm foundation for long-term trend analysis. The dataset will serve as a reference record for inter-calibration



600 with higher-density satellite instruments, including TROPOMI (Hu et al., 2018), and as a benchmark for the next generation of greenhouse-gas monitoring missions including Copernicus CO2M and Sentinel-5.



10 Data availability

The UoL GOSAT-2 Proxy XCH₄ v2.0 dataset described in this work is available from the Centre for Environmental Data Analysis (CEDA) under the DOI <https://doi.org/10.5285/8209b9acb92e4ba69188c9c8ff7a3b76> (Parker et al., 2026a). The data
605 are distributed under the UK Open Government Licence v3.0 (<http://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/>), which is compatible with the Creative Commons Attribution 4.0 Licence. Files are distributed as daily NetCDF4, conforming to CF-1.8. The contents and recommended usage are described in Appendix B. The file-level metadata records the product version, processing date, and bias correction applied. The companion UoL GOSAT Proxy XCH₄ v10.0 dataset used
610 here is described in Parker et al. (2020) and is available from CEDA under the DOI <https://doi.org/10.5285/94d6572a308e477c86e0ce7c4d771311> (Parker et al., 2026b). TCCON data are taken from the GGG2020.1 public release (Wunch et al., 2025; Total Carbon Column Observing Network (TCCON) Team, 2026), available from CaltechDATA via <https://tccodata.org>. The per-site data records are cited in Appendix D.

11 Code availability

The GOSAT-2 Proxy XCH₄ retrieval code is not publicly available, as the processing chain is tightly coupled to the University
615 of Leicester high-performance computing environment, is constrained by licence terms, and is not packaged for external use. The underlying retrieval framework shares significant heritage with the ACOS retrieval algorithm, which is available at <https://zenodo.org/records/14661409>.

Appendix A: Summary of dataset characteristics

Table A1 summarises the headline characteristics of the UoL GOSAT-2 Proxy XCH₄ v2.0 dataset described in this work.
620 The values are reproduced from the body of the paper for quick reference. The corresponding sections give the underlying methodology and context.

Appendix B: Data contents and usage notes

The dataset is distributed as daily NetCDF4 files in CF-1.8 convention, mirroring the structure of the UoL GOSAT v10.0 Proxy product (Parker et al., 2020, 2026b) to support consistent processing across the combined record. Each file contains all
625 quality-filtered soundings for a single day, indexed by sounding number along a single sounding dimension (*n*).

Global attributes record the product version, processing date, retrieval algorithm reference, bias-correction value applied, and a DOI for citation.



Table A1. Summary of the UoL GOSAT-2 Proxy XCH₄ v2.0 dataset.

Attribute	Value
Product	UoL GOSAT-2 Proxy XCH ₄
Version	v2.0
Instrument	TANSO-FTS-2 on GOSAT-2
Temporal coverage	5 February 2019 – 31 December 2025
Spatial coverage	Global
Observation modes	Land nadir, ocean glint
Footprint diameter	9.6 km
Overpass time	13:00 ± 00:15 local
Spectral window	Band 2, ~1.6 μm (CO ₂ + CH ₄)
Retrieval framework	Optimal estimation (Rodgers, 2000)
Model XCO ₂ source	Median of GEOS-Chem, CarbonTracker, CAMS
Total L1B soundings processed	16,549,175
Quality-filtered soundings	4,442,498
Bias correction	−(18.044 + 0.260 · SZA) ppb (cross-anchored to GOSAT)
Mean residual vs TCCON	+5.52 ppb (by construction of the cross-anchor)
σ vs TCCON	16.41 ppb
Pearson <i>R</i> vs TCCON	0.910
TCCON co-locations	135,110 across 24 sites
Data format	NetCDF4 (CF-compliant)
DOI	10.5285/8209b9acb92e4ba69188c9c8ff7a3b76

Recommended usage

The dataset should be filtered to `xch4_quality_flag == 0` before any analysis. Unfiltered soundings include cases where the spectral fit did not converge to acceptable residuals or where post-retrieval thresholds (e.g. on χ^2 or solar zenith angle) were exceeded. Within the quality-filtered subset, land and glint soundings can be combined for global aggregates, but should be treated separately when scene-type biases are of interest. The bias correction described in Sect. 5 has already been applied to `xch4`. The pre-correction Proxy value is retained in `xch4_no_correction`, allowing users to apply alternative bias-correction schemes without reprocessing.

For comparison with model output, the averaging kernel must be applied to the model CH₄ profile interpolated onto the per-sounding pressure grid (Appendix C). Direct comparison without averaging-kernel application is appropriate only when the model profile shape closely matches the a priori shape used in the retrieval.



Table B1. Core variables in the UoL GOSAT-2 Proxy XCH₄ v2.0 NetCDF4 files. All soundings with xch4_quality_flag ≠ 0 should be excluded before analysis.

Variable	Units	Description
time	s	Sounding acquisition time (seconds since 1970-01-01 UTC)
latitude, longitude	degrees	Sounding centre coordinates; longitudes in [−180, 180]
xch4	ppb	Bias-corrected Proxy XCH ₄ ; recommended variable for scientific use
xch4_no_correction	ppb	Proxy XCH ₄ before bias correction
raw_xch4	ppb	Directly retrieved XCH ₄ from the spectral fit (numerator of the Proxy ratio); no bias correction applied
raw_xco2	ppm	Directly retrieved XCO ₂ from the spectral fit
xch4_uncertainty	ppb	Single-sounding posterior uncertainty from optimal estimation
xch4_quality_flag	—	Integer flag; 0 = passed all quality filters
xch4_averaging_kernel	—	Column averaging kernel as a function of pressure level (see Appendix C)
ch4_profile_apriori	ppb	Per-sounding a priori CH ₄ profile
pressure_levels	hPa	Per-sounding pressure grid for averaging kernel and a priori
model_xco2	ppm	Model XCO ₂ used in the Proxy ratio (Eq. (1))
retr_flag	—	Retrieval type flag: 0 = land nadir, 1 = ocean glint
solar_zenith_angle	degrees	Solar zenith angle
sensor_zenith_angle	degrees	Sensor (satellite) zenith angle
exposure_id	—	Unique sounding identifier, derived from the JAXA L1B exposure identifier

The dataset is sparse and non-uniform in space and time, with sampling reduced over persistently cloudy regions and at high latitudes during winter. Spatial and temporal aggregation should account for sampling density to avoid coverage-driven artefacts in regional averages.

Appendix C: Application of GOSAT-2 averaging kernels to model data

Comparison of the retrieved XCH₄ with model output requires the model profile to be transformed onto the satellite’s sensitivity, accounting for the contribution of the a priori profile in the retrieval. Following Rodgers (2000) and the implementation used for GOSAT in Parker et al. (2020), the model-equivalent column is

$$\widehat{\text{XCH}_4}^{\text{mod}} = \sum_{i=1}^{N_{\text{lev}}} \left[\text{VMR}_i^{\text{apr}} + \left(\text{VMR}_i^{\text{mod}} - \text{VMR}_i^{\text{apr}} \right) \text{AK}_i \right] h_i, \quad (\text{C1})$$

where $\widehat{\text{XCH}_4}^{\text{mod}}$ is the model-equivalent column XCH₄ comparable to the satellite retrieval, N_{lev} is the number of pressure levels in the retrieval grid, $\text{VMR}_i^{\text{apr}}$ is the a priori CH₄ dry-air mole fraction at level i (from ch4_profile_apriori),



650 $\text{VMR}_i^{\text{mod}}$ is the model CH_4 mole fraction at the same level interpolated onto the retrieval grid, AK_i is the column averaging kernel at level i (from `xch4_averaging_kernel`), and h_i is the dry-air pressure weighting function (provided as `pressure_weight`). These per-sounding quantities are provided in the distributed NetCDF files as described in Appendix B.

The pressure weighting function h_i satisfies $\sum_i h_i = 1$ and is defined such that, for a perfectly informative retrieval ($\text{AK}_i = 1$ at all levels), Eq. (C1) reduces to the simple pressure-weighted column mean of the model profile. For levels where the averaging kernel departs from unity, the model column is pulled towards the a priori in proportion to the local loss of sensitivity.

655 When the model profile shape matches the a priori shape closely, the correction term in Eq. (C1) becomes small and the model column can be compared directly with the retrieved XCH_4 . In general, however, the averaging-kernel correction is non-negligible and should be applied before computing satellite-minus-model biases, particularly in the lower troposphere where surface emissions drive most of the inter-model spread.

Appendix D: TCCON data

660 All TCCON measurements used in this work are taken from the GGG2020.1 public release of 19 June 2026 (Wunch et al., 2025; Total Carbon Column Observing Network (TCCON) Team, 2026). Table D1 lists the contributing sites together with their geographic coordinates and altitude, time spans and per-site data references.

A small number of sites in the GGG2020.1 release were excluded from the validation reported in Sect. 7 due to either not being representative of the local satellite footprint (high altitude, urban) or not having a sufficient number of matches for a statistically meaningful comparison.



Table D1. TCCON sites used for GOSAT and GOSAT-2 validation in this work. Coordinates and altitudes are taken from the GGG2020.1 public.qc.nc files. Period gives the date range of measurements available in the GGG2020.1 release. The Reference column cites the per-site GGG2020.1 data record. The full citations, including the per-site DOIs, are given in the reference list.

Site	Location	Code	Lat (°N)	Lon (°E)	Alt (m)	Period	Reference
Eureka	Canada	eureka01	80.05	−86.42	610	Jul 2010–Jul 2020	Strong et al. (2026)
Ny-Ålesund	Svalbard (NO)	nyalesund01	78.92	11.92	20	Mar 2005–Jun 2025	Buschmann et al. (2026)
Sodankylä	Finland	sodankyla01	67.37	26.63	188	May 2009–Oct 2025	Kivi et al. (2026)
East Trout Lake	Canada	easttroutlake01	54.36	−104.99	495	Oct 2016–May 2026	Wunch et al. (2026)
Bialystok	Poland	bialystok01	53.23	23.02	185	Mar 2009–Oct 2018	Petri et al. (2026a)
Bremen	Germany	bremen01	53.10	8.85	30	Feb 2006–May 2025	Notholt et al. (2026)
Harwell	UK	harwell01	51.57	−1.32	129	May 2021–Mar 2026	Weidmann et al. (2026)
Karlsruhe	Germany	karlsruhe01	49.10	8.44	110	Jan 2014–Dec 2024	Hase et al. (2026)
Paris	France	paris01	48.85	2.36	60	Sep 2014–Dec 2025	Té et al. (2026)
Orléans	France	orleans01	47.96	2.11	130	Sep 2009–Apr 2025	Warneke et al. (2026)
Garmisch	Germany	garmisch01	47.48	11.06	743	Jul 2007–Jan 2024	Sussmann et al. (2026)
Park Falls	USA	parkfalls01	45.94	−90.27	476	Jun 2004–Feb 2026	Wennberg et al. (2026a)
Rikubetsu	Japan	rikubetsu01	43.46	143.77	380	Jun 2014–Jun 2025	Morino et al. (2026a)
Xianghe	China	xianghe01	39.80	116.96	40	Jun 2018–Dec 2024	Zhou et al. (2026)
Lamont	USA	lamont01	36.60	−97.49	320	Apr 2011–Feb 2026	Wennberg et al. (2026b)
Tsukuba (125HR)	Japan	tsukuba02	36.05	140.12	31	Mar 2014–Mar 2021	Morino et al. (2026b)
Nicosia	Cyprus	nicosia01	35.14	33.38	185	Sep 2019–Jun 2025	Petri et al. (2026b)
Edwards	USA	edwards01	34.96	−117.88	700	Jul 2013–Feb 2026	Iraci et al. (2026)
Saga	Japan	saga01	33.24	130.29	9	Jul 2011–Dec 2023	Shiomi et al. (2026)
Hefei	China	hefei01	31.90	117.17	40	Nov 2015–Dec 2025	Liu et al. (2026)
Burgos	Philippines	burgos01	18.53	120.65	40	Mar 2017–Apr 2025	Morino et al. (2026c)
Darwin	Australia	darwin01	−12.42	130.89	30	Jan 2013–Jul 2025	Deutscher et al. (2026b)
Réunion Island	Réunion (FR)	reunion01	−20.90	55.48	85	Mar 2015–Jul 2020	De Mazière et al. (2026)
Wollongong	Australia	wollongong01	−34.41	150.88	30	Jan 2013–Mar 2026	Deutscher et al. (2026a)
Lauder (125HR)	New Zealand	lauder02, lauder03	−45.04	169.68	370	Feb 2010–Jun 2025	Sherlock et al. (2026), Pollard et al. (2026)

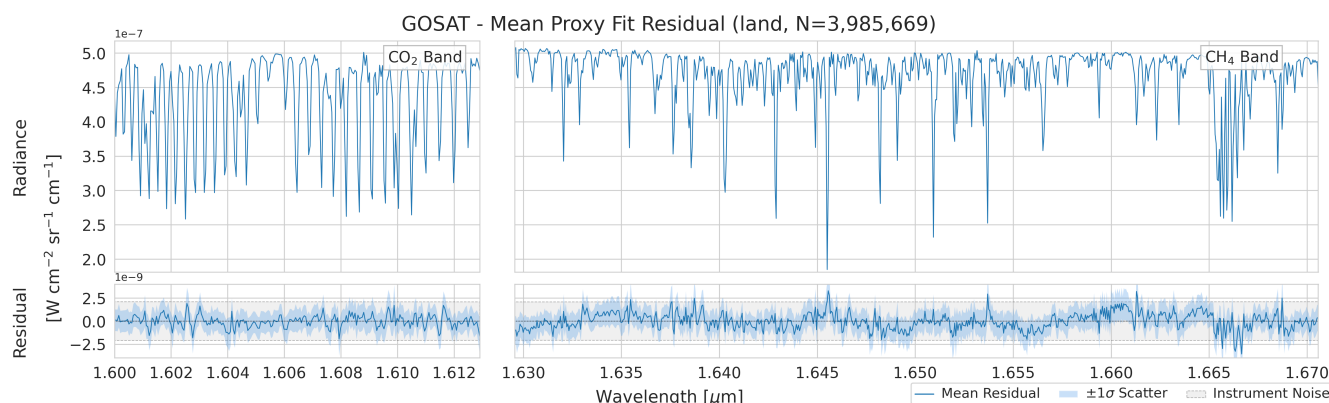


Figure E1. As Fig. 1 but for the GOSAT Proxy fit over its full quality-filtered land record ($N = 3,985,669$ soundings).

665 Appendix E: GOSAT mean fit residual

The mean Proxy fit residual for GOSAT, computed over its full quality-filtered land record ($N = 3,985,669$ soundings) with the same procedure used for GOSAT-2 (Sect. 3.3), is shown in Fig. E1. Its amplitude and structure are comparable to those of GOSAT-2 (Fig. 1), with which the residual shape correlates at $r = 0.46$ (CO_2) and $r = 0.74$ (CH_4).

Appendix F: Quality filter thresholds

670 Table F1 lists the full set of quality filter criteria applied to both the GOSAT v10.0 (Parker et al., 2020, 2026b) and GOSAT-2 v2.0 Proxy XCH_4 retrievals. Thresholds were optimised against TCCON validation data for each instrument separately, following Parker et al. (2020). The wider χ^2 bounds for GOSAT-2 do not indicate poorer spectral fits. Systematic effects such as spectroscopic uncertainties set a floor on the fit residual that is comparable for the two instruments (Sect. 3.3), while the noise entering χ^2 , estimated from the out-of-band signal, is lower for TANSO-FTS-2, so the same residual amplitude yields a larger
 675 residual-to-noise ratio. This elevation is concentrated in the CO_2 fit window and over bright scenes rather than uniform across the data. The wider posterior error bound for GOSAT-2 is a loose filter rather than a sign of larger errors. Typical reported errors are smaller for GOSAT-2 than for GOSAT, consistent with its lower noise, and the error criterion excludes 1.1 % of retrieved GOSAT-2 soundings against 11.7 % for GOSAT. The resulting validation performance is closely comparable for the two products, with standard deviations against TCCON of 16.41 and 16.42 ppb (Sect. 7).



Table F1. Quality filter thresholds for the UoL GOSAT v10.0 and GOSAT-2 v2.0 Proxy XCH₄ products. All criteria within each group must be satisfied. Soundings passing all groups receive quality flag 0 (good). The cloud-screening filter is applied prior to retrieval. All other filters act on the retrieval output.

Filter criterion	GOSAT	GOSAT-2
<i>Pre-retrieval cloud screen</i>		
Surface pressure residual ($ p_{\text{retr}} - p_{\text{ERA5}} $)	≤ 30 hPa	≤ 30 hPa
<i>Spectral fit quality</i>		
CH ₄ band-2 χ^2	0.4–1.9	0.4–3.0
CO ₂ band-2 χ^2	0.4–1.9	0.4–5.0
<i>Posterior retrieval errors</i>		
XCH ₄ posterior error	≤ 20 ppb	≤ 40 ppb
XCO ₂ posterior error	≤ 3 ppm	≤ 6 ppm
<i>Retrieved state bounds</i>		
Retrieved XCH ₄	≥ 1650 ppb	≥ 1650 ppb
Retrieved XCO ₂	≥ 350 ppm	≥ 350 ppm
<i>Auxiliary</i>		
Latitude	$\geq -60^\circ$	$\geq -60^\circ$
Solar zenith angle	—	$< 75^\circ$
Band-1 SNR (P-polarisation)	≤ 300	≤ 300
Model median XCO ₂	≤ 1000 ppm	≤ 1000 ppm
<i>Convergence and validity (CH₄ and CO₂)</i>		
Retrieval outcome flag	= 1	= 1
Iteration convergence achieved	yes	yes
Cost-function divergence	no	no



680 Appendix G: Comparison against EM27/SUN measurements at Jinja, Uganda

Assessing satellite XCH₄ biases in the tropics is difficult because ground-based validation measurements there are scarce. The TCCON stations used to derive and evaluate the bias corrections of Sect. 5 lie predominantly in the northern mid-latitudes (Appendix D), so the corrections are anchored to observing conditions that differ from those of tropical scenes, despite the importance of tropical sources such as wetlands to the global CH₄ budget. To provide an independent tropical assessment, we
 685 compare both products against measurements from the EM27/SUN Fourier transform spectrometer (instrument SN059) that we operate at Jinja, Uganda (0.42° N, 33.21° E; 1157 m a.s.l.), on the northern shore of Lake Victoria (Humpage et al., 2024). The quality-filtered XCH₄ record comprises 14,680 retrievals on 134 measurement days between January 2020 and November 2025, acquired in three campaigns (January–May 2020, July–September 2023, and July–November 2025).

Satellite soundings are co-located with the EM27/SUN record using the same criteria as for TCCON (Sect. 4.3): soundings
 690 within $\pm 5^\circ$ of the site are paired with the mean of all EM27/SUN measurements within ± 2 hours of the mean satellite overpass time on each day. Figure G1 shows the comparison for the bias-corrected products. We find a mean satellite-minus-EM27/SUN difference of -3.27 ppb for GOSAT ($\sigma = 15.88$ ppb, $R = 0.801$, $N = 381$ soundings on 51 days) and $+1.42$ ppb for GOSAT-2 ($\sigma = 14.57$ ppb, $R = 0.849$, $N = 601$ soundings on 58 days). Without the bias corrections the equivalent differences are $+13.39$ ppb and $+24.50$ ppb. The corrections, derived entirely from TCCON and the inter-instrument matched pairs with no
 695 input from this site, therefore remove almost all of the offset at Jinja, and the single-sounding scatter is comparable to that found against the TCCON network (Sect. 7). This suggests that the corrections transfer well to tropical conditions. We note that, relative to their network-mean TCCON residuals (Sect. 5), both instruments read 3–4 ppb lower at Jinja, which may partly reflect the predominantly northern mid-latitude distribution of the TCCON sampling, although a single site cannot establish this.

700 Figure G2 shows the satellite sampling around the site. Both instruments observe this region densely. The full quality-filtered records contain 16,377 GOSAT and 13,211 GOSAT-2 soundings within the $\pm 5^\circ$ co-location window. The constraint on any tropical bias assessment is instead the ground-based record, which at present covers 134 measurement days across the three campaigns, of which 51 (GOSAT) and 58 (GOSAT-2) provide co-locations. Continued operation of the Jinja station will extend this record and allow a more complete tropical assessment in future.

705 The difference between the GOSAT and GOSAT-2 statistics in Fig. G1 could reflect either a genuine inter-instrument inconsistency over this region or simply the different sampling of the two records, which share only a subset of days and scenes. To separate these possibilities we apply the matched-pair criteria of Sect. 4.3 (footprint centres within 5 km, observation times within 1 hour, both soundings quality-filtered) to the region around Jinja. Within $\pm 10^\circ$ of the site this gives 2,770 GOSAT-to-GOSAT-2 pairs on 583 days between February 2019 and December 2025. The wider window is used to accumulate sufficient
 710 pairs, and the sparser $\pm 5^\circ$ subsample (137 pairs, $+4.07$ ppb, $\sigma = 9.15$ ppb, $R = 0.932$) behaves consistently. The bias-corrected pairs agree closely (Fig. G3), with a mean GOSAT-2 minus GOSAT difference of $+1.42$ ppb, $\sigma = 10.51$ ppb, and $R = 0.953$. The inter-instrument correlation is substantially higher than either instrument's correlation against the EM27/SUN, and the mean difference is small. This implies that the two products are consistent with one another over this region when compared

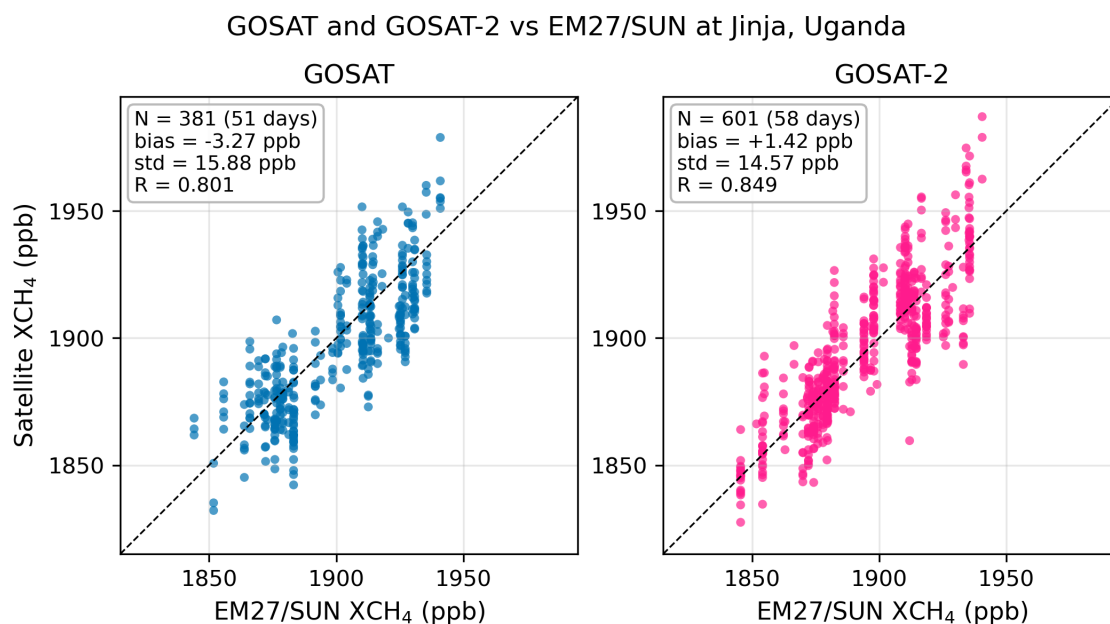


Figure G1. Bias-corrected GOSAT (left, blue) and GOSAT-2 (right, magenta) XCH₄ against co-located EM27/SUN measurements at Jinja, Uganda. Each point pairs one quality-filtered satellite sounding within $\pm 5^\circ$ of the site with the mean of all EM27/SUN measurements within ± 2 hours of the mean overpass time on that day (Sect. 4.3). The dashed line is the 1:1 relation. Annotations give the number of matched soundings (and days), the mean satellite-minus-EM27/SUN difference, its standard deviation, and the correlation coefficient.

like-for-like, and that the differences between their EM27/SUN statistics in Fig. G1 primarily reflect sampling rather than
 715 instrument behaviour.

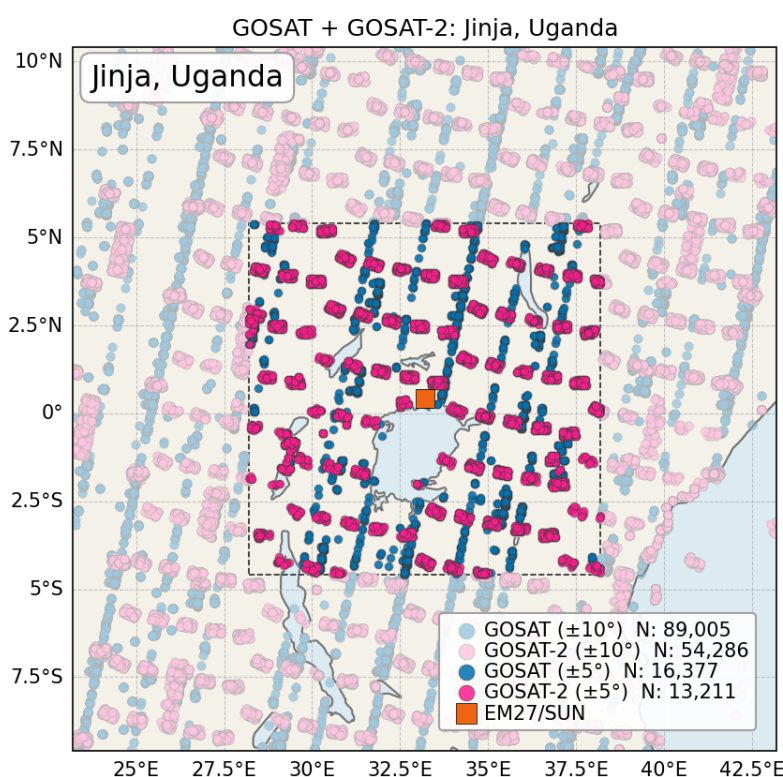


Figure G2. Spatial distribution of quality-filtered GOSAT (blue) and GOSAT-2 (magenta) soundings around the Jinja EM27/SUN station (orange square), in the style of Fig. 4. Filled circles show soundings within the $\pm 5^\circ$ co-location window (dashed box) over each instrument's full record (GOSAT April 2009–December 2025; GOSAT-2 February 2019–December 2025). Lighter points show the wider $\pm 10^\circ$ context. Legend values (N) are the total quality-filtered soundings in each window.



Footprint-matched GOSAT-2 vs GOSAT: joint KDE (within $\pm 10^\circ$ of Jinja)

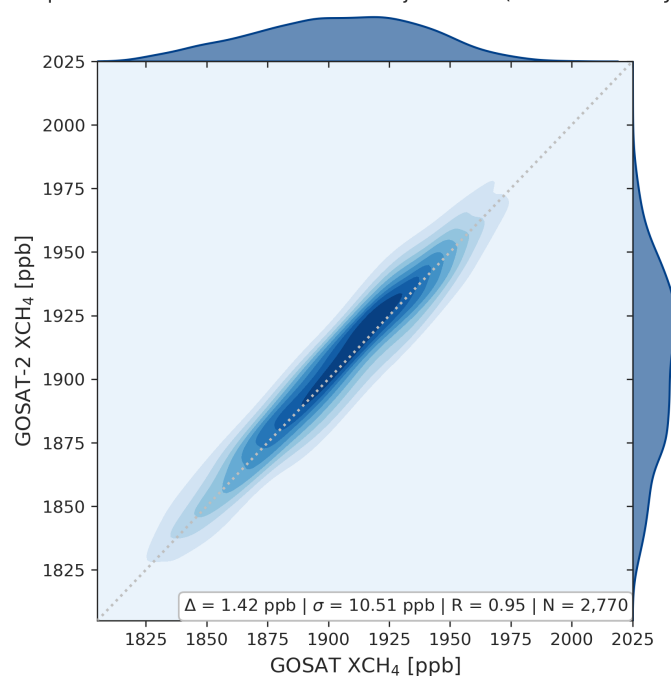


Figure G3. Joint kernel density estimate of bias-corrected GOSAT-2 against GOSAT XCH₄ for the matched-pair sample (footprint centres within 5 km, observation times within 1 hour; Sect. 4.3) within $\pm 10^\circ$ of the Jinja site. The dotted line is the 1:1 relation. The annotation gives the mean GOSAT-2 minus GOSAT difference (Δ), its standard deviation (σ), the correlation coefficient, and the number of pairs. Marginal distributions are shown along the axes.



Appendix H: Sampling considerations when comparing GOSAT and GOSAT-2

The two instruments do not sample the atmosphere identically. GOSAT-2 observes with a 6-day repeat cycle against 3 days for GOSAT, applies real-time intelligent pointing over land (Sect. 2.2), and allocates part of its observation schedule to targeted sites, while the seasonal high-latitude coverage of the two records also differs. Monthly or regional aggregates computed from each record therefore average over different scene populations, and apparent inter-instrument differences can arise from sampling alone.

Figure H1 quantifies this effect by restricting both instruments to the footprint-matched sample of Sect. 4.3 (pairs within 5 km and 1 hour; $N = 124,206$), globally and in three latitude bands. Under common sampling the two records agree closely. The global monthly-mean difference is $+0.04$ ppb with a month-to-month standard deviation of 1.52 ppb, compared with $+1.33$ and 3.29 ppb when each instrument's full sampling is used (the inset of Fig. 14), and the apparent seasonal oscillation of the full-sampling difference is removed. The effect on individual months is substantial. Under full sampling the monthly difference reaches $+9.5$ ppb, and 12 of the 83 overlap months exceed 5 ppb, with the largest differences in boreal winter months. Under matched sampling no month exceeds 3.7 ppb. Band-mean differences are $+1.26$ ppb over 30 – 60° N, -1.19 ppb over 30° S– 30° N and $+1.31$ ppb over 30 – 60° S. Poleward of 60° N the matched sample is small ($6,521$ pairs, observed at high SZA) and the mean difference is larger at $+4.82$ ppb. We note that matched footprints are not strictly identical air masses, as the two instruments view each scene with different geometry, so the residual differences combine instrument-level effects with any viewing-geometry sensitivity.

Care is therefore needed when comparing the two records, or when interpreting features of the combined record, during the overlap period. Differences should be assessed on common spatio-temporal sampling, either the footprint-matched sample used here or co-located grid-cell means (Sect. 8), before any residual is attributed to instrument behaviour. This applies in particular to apparent differences in seasonal-cycle amplitude and phase, where the sampling-driven component of the full-record difference is largest.

Appendix I: GOSAT-2 operational event history

Table I1 summarises the operational events that interrupted or affected TANSO-FTS-2 observation during the study period. Where two events occurred in the same month they are condensed into a single row. The impact of these events on monthly sounding counts is discussed in Sect. 2.3.

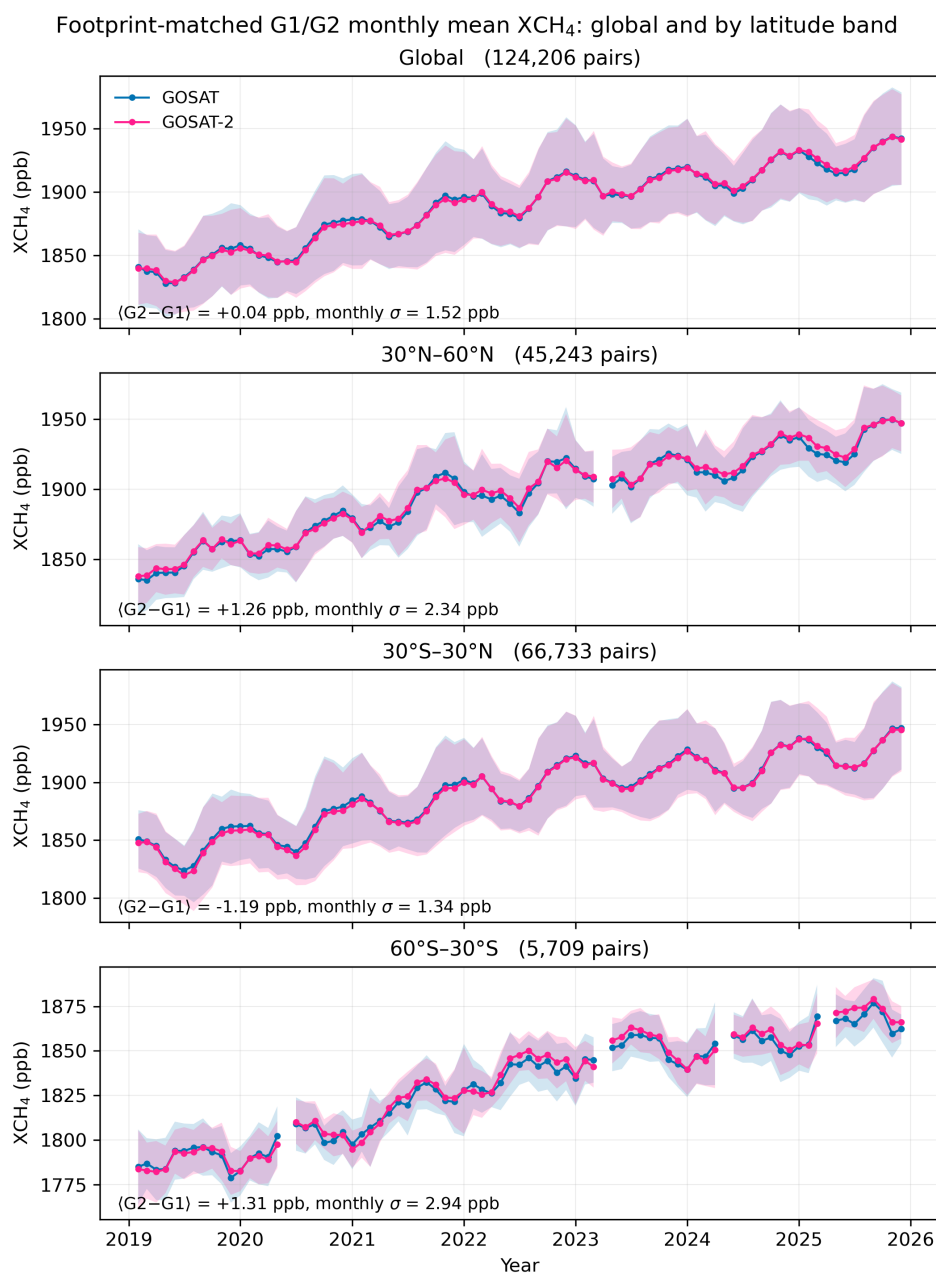


Figure H1. Monthly mean bias-corrected Proxy XCH₄ from GOSAT (blue) and GOSAT-2 (magenta) over 2019–2025, restricted to the footprint-matched sample (footprint centres within 5 km, observation times within 1 hour, quality-filtered; Sect. 4.3; N = 124,206 pairs), shown globally and for three latitude bands. Shading gives the $\pm 1\sigma$ within-month spread. Band-months with fewer than 25 pairs are excluded. Annotations give the mean and month-to-month standard deviation of the monthly GOSAT-2 minus GOSAT difference.



Table 11. Operational events affecting TANSO-FTS-2 observation over the study period (February 2019 to December 2025).

Date	Event	Observations suspended
Apr 2019	Two separate debris-avoidance orbit-control manoeuvres	5 days each
Feb 2020	Two separate switches to diagnostic mode	10 and 4 days
Mar 2021	Switch to safe mode	7 days
Jun 2021	Two separate switches to safe mode	3 days each
Aug 2021	Switch to diagnostic mode	3 days
Sep–Oct 2021	Inclination-control orbit campaign	22 days
Jan 2023	Orbit-control manoeuvre (routine maintenance)	5 days
May–Jun 2024	Out-of-plane orbit-control campaign	29 days
Sep 2024	Switch to diagnostic mode	7 days
Dec 2024	Switch to diagnostic mode	4 days
Feb 2025	Switch to diagnostic mode	4 days



Author contributions. RJP led the study and drafted the manuscript. RJP, MPC, and DO developed and maintained the GOSAT-2 Proxy XCH₄ processing chain and produced the v2.0 product. RJP carried out the validation against TCCON and the comparison with GOSAT. LNB contributed to the post-retrieval quality filtering. NH contributed to the validation against EM27/SUN measurements. AJW, PS, HB and
 745 ADN contributed to the development and testing of the retrieval algorithm and its ancillary inputs. HS supported the use of the GOSAT and GOSAT-2 data and the interpretation of the GOSAT-2 biases. The TCCON co-authors operated the contributing TCCON sites, performed the GGG2020 retrievals, and provided validation data. All authors contributed to the writing and review of the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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