# Authors' answer to the interactive comments of anonymous referee #1 on "Long-term column-averaged greenhouse gas observations using a COCCON spectrometer at the high surface albedo site Gobabeb,Namibia" by Frey et al., Atmos. Meas. Tech. Discuss., amt-2020-444

First of all, we would like to thank the anonymous referee #1 for the help in further improving the manuscript by a thorough assessment with regards to content and the careful technical proofreading resulting in the identification of several imprecisions. Referee comments are in *blue italic*, responses in black. Changes in the manuscript are in *green italic*.

## 1 Overview

*It is great to see the start of long-term measurements of ground-based column-averaged greenhouse gases from the African continent; these measurements promise to be a valuable addition for satellite validation and carbon cycle science. The measurements to compare between GOSAT M- and H-gain retrievals are rare, and it is useful to see previously observed biases confirmed. It will be good to see these data made available to the scientific community.*
*In general, the work presented here is of good quality. While the language could be improved in many places, I don't find that there are many instances where the meaning is unclear and therefore the paper is understandable.*
*I recommend publication to AMT after addressing a number of changes.*
*None are major, but many are still important to address.*

We thank the referee for this positive feedback and we will address the comments given below. We also appreciate the patience of the referee concerning the language-related issues of the manuscript and the corrections provided.

## 2 General comments

Do you assess the Gobabeb data for potential airmass dependences?

In Figure 9 of the original manuscript we show the intraday variability of several days of measurements from the COCCON station in Gobabeb and the closest TCCON station, Reunion Island. We discuss that a small residual airmass dependency is apparent for $XCO_2$ and $XCH_4$. The magnitude of this airmass dependency is similar for the COCCON instrument and the TCCON instrument, which we consider best available reference for ground-based remote sensing.

For the CAMS evaluation, one could argue that restricting based on solar zenith angle rather than time is a better approach. Did you consider this?

When we only take the noon data into account, we effectively also restrict the SZA to values between 0° (SZA in Southern hemispheric summer) and 50° (SZA in Southern hemispheric winter). When taking all hourly data into account, we allow SZAs from 0° to 80° (we only evaluate COCCON data with SZAs up to 80° - this selection is included for limiting possible airmass dependent artifacts, which might be introduced by the data analysis or the measurement process itself). Note, that due to the low latitude of the site, the solar elevation is changing much faster during the day than in temperate latitudes. The sun travels through the elevation range between 80° and 50° SZA in just about two hours. Therefore, in our opinion the approach to restrict the comparison to specific SZAs is almost similar to our approach of restricting the comparison based on time. As we describe in section 4.3, the difference between COCCON and CAMS when considering all hourly data and only using the data from local noon is 0.2 ppm for $XCO_2$ and 2 ppb for $XCH_4$.

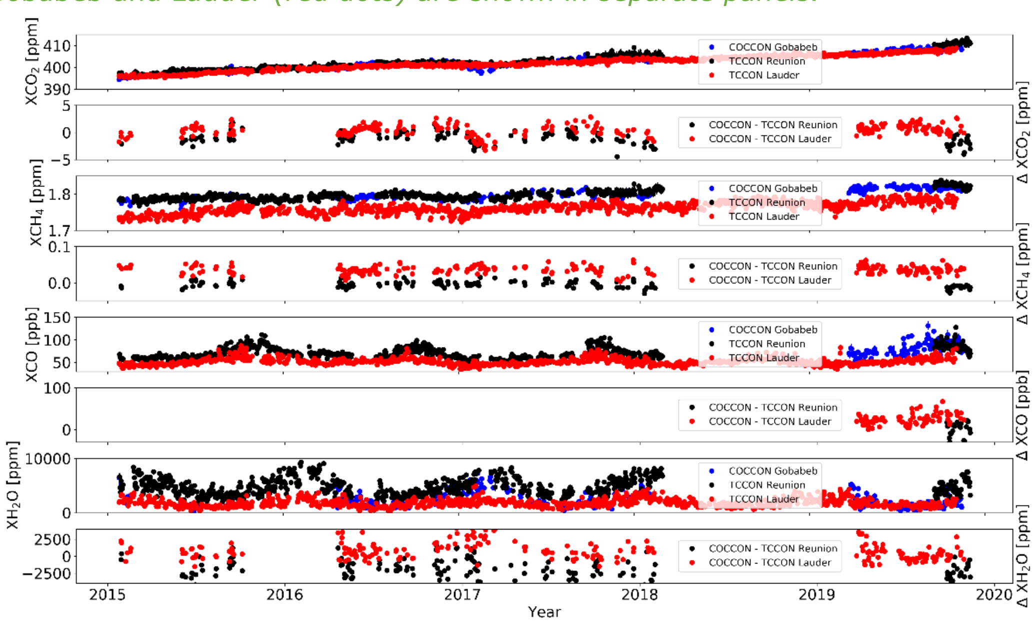
While the paper is understandable, it could be revised to be a bit more clearly written.

We revised the paper and eliminated imprecisions. We especially restructured section 4.1 to focus only on the COCCON/TCCON comparison. We now discuss the origins of the low $XCO_2$ values observed in Gobabeb in a separate section.

For comparisons, it would also be good to see some plots of the differences as well as the scatter plots or comparative time series.

We added difference plots to the COCCON TCCON comparisons:

Figure R1: Column-averaged dry air mole fraction daily mean time series for $XCO_2$, $XCH_4$, XCO and $XH_2O$ measured at the COCCON site in Gobabeb, Namibia (blue dots) and at the TCCON sites Reunion Island (black dots) and Lauder (red dots). Error bars denote the 1 σ standard deviation of the daily mean values. *Additionally, the difference $XCO_2$, $XCH_4$, XCO and $XH_2O$ timeseries between Gobabeb and Reunion Island (black dots) and between Gobabeb and Lauder (red dots) are shown in separate panels.*



The comparisons to Reunion and Lauder TCCON sites are somewhat reassuring, but also complicate matters. This is particularly true for the period where $X_{CO_2}$ disagrees between Gobabeb and Reunion, in early 2017. I find the postulated explanation and evidence for this unconvincing. I'm not suggesting it isn't the correct reason, just that it's not well-enough supported. I therefore suggest that the authors focus on eliminating instrument problems as a cause of the difference, which should be easy enough given the other gases don't deviate and the $X_{air}$ is stable. Then leave the potential explanation as a hypothesis only and something that warrants further investigation to link it to African biosphere fluxes. Otherwise, at least examination of the CAMS posterior fluxes should be included.

As requested by the referee, we further evidence that the differences seen in early 2017 are very likely not due to instrumental issues. Additionally, as suggested by the referee we now also provide CAMS posterior fluxes to further back up our hypothesis that the differences are linked to the African biosphere. As mentioned above, we restructured this section. In section 4.1 we now focus on the COCCON/TCCON comparison. We added section 5, where we elaborate on our hypothesis about the origin of the low $XCO_2$ values observed in Gobabeb:

*From the end of 2016 until the beginning of 2017, the $XCO_2$ values at the COCCON station at Gobabeb were significantly lower compared to the TCCON stations Reunion Island and Lauder, see section 4.1. We rule out instrumental problems as the reason, as $X_{air}$ is stable and the other observed gases do not show abnormal variations during this period. In order to investigate whether the drawdown of $XCO_2$ at the beginning of 2017 at the Gobabeb station is linked to the African biosphere, in Fig. R2 we present global OCO-2 assimilated CAMS a posteriori surface carbon fluxes for 16 February 2017 12 UTC, the day with the lowest $XCO_2$ values in 2017. We find that in the direct vicinity of Gobabeb, no strong negative carbon fluxes are apparent. From this, we deduce that air parcels with low $CO_2$ concentrations are transported to Gobabeb from other regions of the African mainland with negative surface fluxes. We therefore expect that the drawdown of $XCO_2$ is driven by low $CO_2$ concentrations in higher layers of the atmosphere that are representative for medium- or long-range transport. This is in agreement with the results of section 4.3, where a comparison between COCCON data with CAMS model data shows that the CAMS model version assimilating total column data reproduces the $XCO_2$ drawdown, in contrast to the version assimilating in situ data only. We grant the possibility that the discrepancy between the different CAMS products could also stem from imperfections of the CAMS model.*
*In Fig. 5, we show 10-day backward trajectory ensemble simulations from the National Oceanic and Atmospheric Administration (NOAA) HYSPLIT model (Stein et al., 2016) for 16 February 2017. Initial 3-hourly meteorological input data is provided by the NCEP Global Data Assimilation System (GDAS) model on a 1 degree latitude-longitude grid. The end point of the trajectory analysis is chosen at a height of 5000 m above ground level. All trajectories exhibit a long dwell time over the African continent in regions with strong negative carbon surface fluxes, see Fig. R2. This corroborates the conjecture that the low $XCO_2$ values at Gobabeb are due to the influence of the African biosphere. Most of the trajectories that arrive at 5000 m height at Gobabeb originate from significantly lower levels of the atmosphere, close to the surface, and are then uplifted, as can be seen in the lower panel of Figure 5.*
*In contrast, the backward trajectories for Reunion Island shown in Fig. 6 dwell almost exclusively over the ocean. In Fig. R3 we additionally provide backward trajectories for Gobabeb ending at 1000 m above ground level. In contrast to the trajectories at 5000 m, these originate from the ocean.*

*Figure R2: Global map showing OCO-2 assimilated CAMS a posteriori surface carbon fluxes for 16 February 2017 12 UTC.*

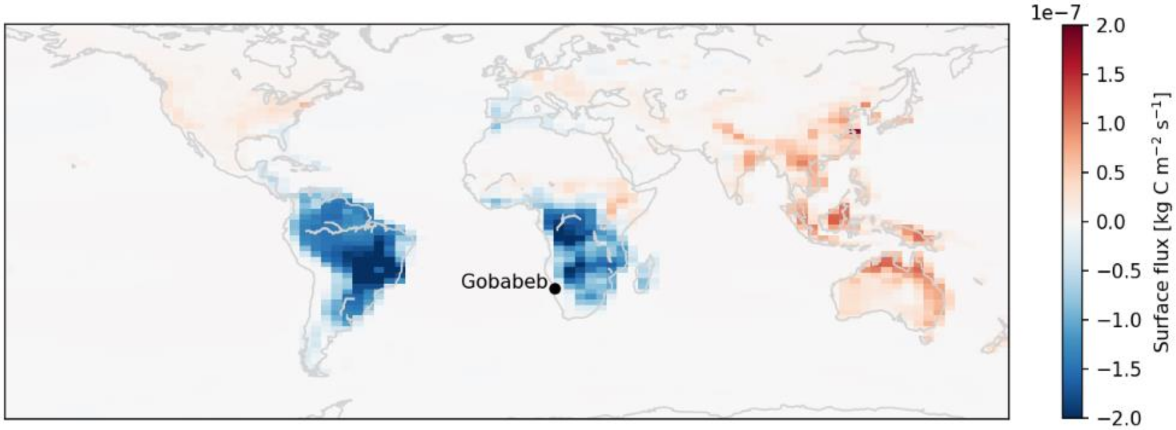
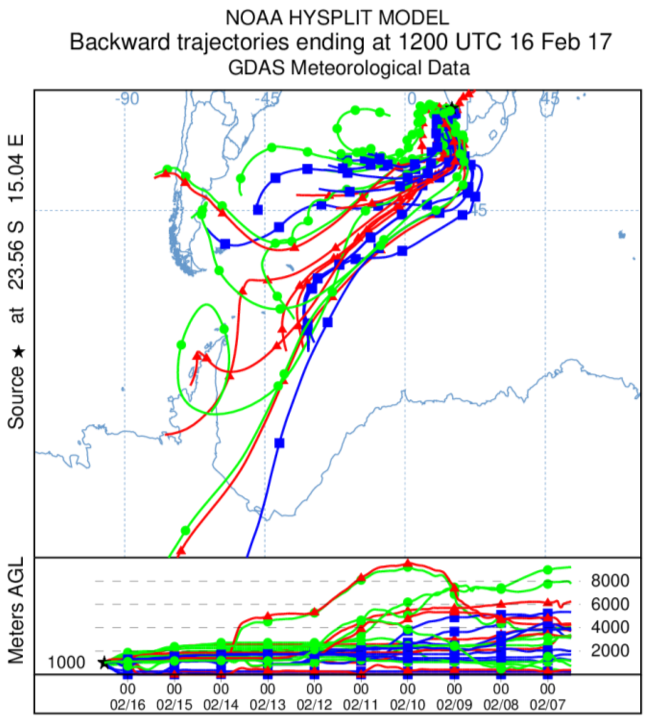



*Figure R3: NOAA HYSPLIT backward trajectory ensemble simulations on 16 February 2017. The endpoint of the backward trajectories is the COCCON Gobabeb station, 1000 m above ground level. The colors and symbols are used to make the different trajectories of the ensemble distinguishable.*




I missed an explanation of the data gaps early in the time series.

The data gap between February and May 2015 was due to software problems. It took so long to figure this out because at the start of the collaboration, there were communication problems between Karlsruhe and Gobabeb. The data gap between October 2015 and April

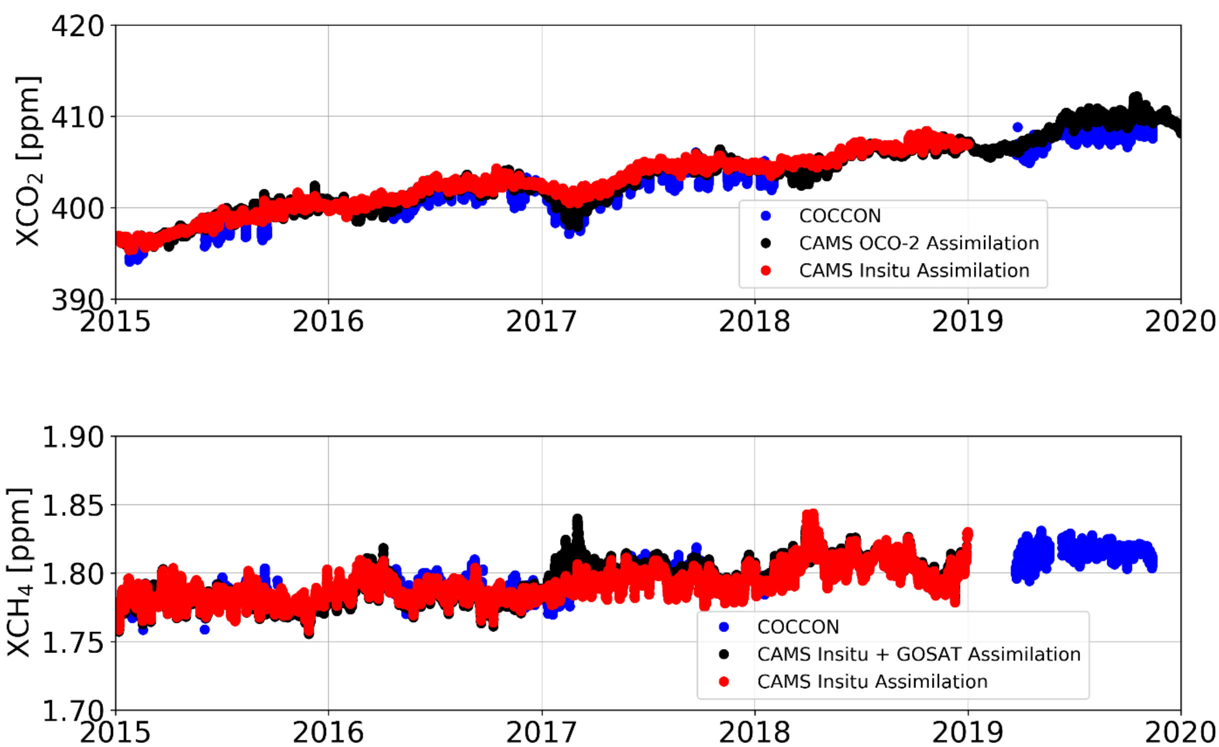
2016 was induced by customs regulations and associated delays. Therefore, we had to ship the instrument back to Karlsruhe temporarily. We added this information in the text:

*Between February and May 2015, no measurements could be performed due to software problems. In October 2015, the spectrometer was shipped back to Karlsruhe due to custom issues. Observations in Gobabeb were continued from April 2016. In February 2018 the spectrometer was shipped to Karlsruhe for the dual channel upgrade. COCCON measurements were restarted in March 2019.*

It might be useful to present time series of the COCCON-CAMS comparisons and their differences.

We included comparative time series between COCCON and the different CAMS datasets in section 4.3.

*Figure R4: Column-averaged dry air mole fraction daily mean time series for $XCO_2$ and $XCH_4$ at Gobabeb, Namibia. COCCON measurements are shown as blue dots, CAMS model data as red and black dots. For COCCON, we show hourly pooled data, for CAMS we show 3-hourly model output for $XCO_2$ and 6-hourly model output for $XCH_4$.*




# 3 Specific comments

l31: sentence order - switch unprecedented and values

Done

l32: delete "it was stated" and "that"

Done

l35: "directly" might be overselling as you would need more than just the measurements themselves, so perhaps delete that word

Ok, done

l43-44: change to "and CO; however, the measurements ..."

Ok

l52: instrument → network

Ok

l84-85: do you have data to illustrate or support the high albedo?

We added albedo information from the GOSAT retrievals and the following text:

*Gobabeb is a high albedo station, with a surface albedo derived from GOSAT retrievals at 1.6 µm of 0.4 for the sand desert and 0.45 for the gravel plains.*

l96: "parts ... were"

Done

l122 - 129: as this is different, it would be good to highlight the differences, and be more specific about the quality control/filtering applied

The analysis is different as we use a new FORTRAN based preprocessing application instead of the previously used python tool. The new source-open tool has been developed in the framework of the ESA project COCCON-PROCEEDS to serve the needs of the COCCON community. Furthermore, we use the recently developed PROFFAST retrieval algorithm, instead of PROFFIT. This code is also source-open and has been created for efficient processing of large numbers of spectra, as the cadence of measurements achieved with low-resolution spectrometers is very high. We expanded our explanation, added a table with the quality filters and reworded as follows:

*Several quality filters are applied, for example requiring a minimum DC level of 5 % of the maximum detector signal level, restricting the tolerable DC variation to 10 % of the DC level of the measured, checking the centerburst location in the IFG and the centerburst amplitudes of forward and backward scans and the relative amplitude of out-of-band artifacts. Table 1 summarizes all quality filters…*
*…PROFFAST is a source-open code for quantitative trace gas analysis, mainly intended for the use with low-resolution FTIR spectrometers. Particular attention has been paid to achieve high processing speed without compromising the high level of accuracy required in the analysis of column-averaged greenhouse gas abundances. For achieving this goal, several measures are taken: (1) PROFFAST uses daily precalculated and tabulated molecular cross-sections derived from line-by-line calculations. (2) Instead of storing the cross sections per discrete layers, the cross-sections are expanded as function of solar*

*zenith angle (SZA), which allows downsizing of the lookup tables by a factor of about five and accelerating the subsequent calculation of atmospheric spectral transmission as function of SZA. (3) The process of convolution of the monochromatic spectrum with the instrumental line shape (ILS) is formulated as a two-step procedure, the first step thins the spectral grid before the convolution is performed. (4) The state vector of the previous solution is maintained for fitting the next spectrum, as typically the atmospheric variations from spectrum to spectrum are rather small. This strategy allows reducing the number of required iterations to typically two. (5) PROFFAST provides averaging kernels not for each measurement, but as function of a set of SZA values for each measurement day.*
*…*

*Table 1*

| | |
|---|---|
| *Q1* | *Check of DC level as fraction of ADC range, require 0.05* |
| *Q2* | *Check maximum variability of DC level (max. 10 % relative variation in interferogram resulting from 10 coadded scans)* |
| *Q3* | *Check FWD / BWD centerburst amplitudes (should agree within 5 %)* |
| *Q4* | *Check centerburst location in interferogram record* |
| *Q5* | *Check relative amplitude of out-of-band artifacts* |
| *Q6* | *Check slope, curvature, and change of curvature of phase spectrum* |
| *Q7* | *Check spectral calibration based on cross-correlation of spectral structure wrt a wavenumber-calibrated reference spectrum* |
| *Q8* | *Compare spectra derived from forward and backward scans* |

l144: good to know there are plans to extend comparisons to other sites

For example, we also now have a long-term time series of COCCON measurements at the TCCON site Tsukuba that will be used in the future.

l149: TCCON doesn't require 0.0035 $cm^{-1}$ spectral resolution, and indeed some instruments don't have that.

We reworded our statement:

*…which is routinely operated at a spectral resolution of 0.02 $cm^{-1}$…*

l156: you could update to reflect the Pollard et al (2021) publication comparing the Lauder instruments

Done

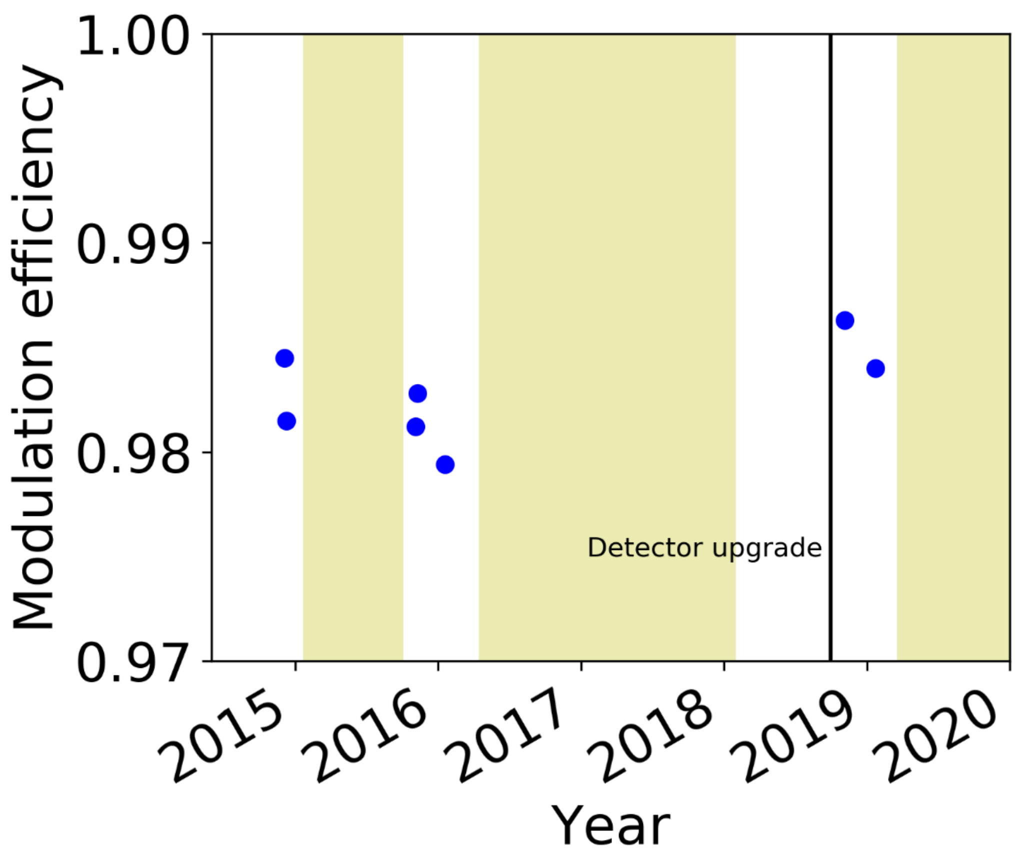
l171: fix location of "e.g." - either inside parentheses with the references, or bring the citations out of the parentheses.

Done

l181-184: a time-series plot of ME @ Max OPD might be nice to support your statements

We added a time series plot of the modulation efficiency.

*Figure R5: Timeseries of the modulation efficiency at MOPD of the EM27/SUN used in this study. ILS measurements were performed during periods when the instrument was in Karlsruhe for maintenance or detector upgrade. Yellow areas denote measurement periods in Gobabeb. The black bar denotes the time of the detector upgrade.*




l184: "not self-evident" - please clarify/revise wording.

We reworded the sentence:

*This high instrumental stability is remarkable considering that between measurements the EM27/SUN was shipped from Karlsruhe to Gobabeb, including airlift and transport by car on bumpy gravel roads.*

l338: while I assume that the bias referred to is between all data and noon-only data, it's not 100% clear, as it could equally apply to bias relative to CAMS. I suggest reworking this sentence: "Although using all COCCON data results in only a small bias of 0.2 ppm for $XCO_2$ and 2 ppb for $XCH_4$ relative to the noon-only data, ..."

Thanks. We reworded as suggested.

l347: "The absolute values..." - sentence needs revision. "The biases between the CAMS model simulation and the Gobabeb measurements are presented in Table 4." (or something like that)

We reworded the sentence accordingly.

l349-350: aren't the end of 2016 and beginning of 2017 the same? I suggest "At the end of 2016 into the beginning of 2017..."

This is true. We reformulated as suggested.

I suggest combining Tables 2 and 3 to make it easier for the reader to compare between M- and H-gains

Ok, done

Figure 1 - I have 2 comments. Firstly some broader context would be useful. Secondly, while there are clearly visible differences between the terrain to the NE and SW of the site, it would be nice to have some indicative albedos at the relevant wavelengths.

We added a world map showing the COCCON and TCCON station used in this study. We also added information about the albedo in the text:

*Gobabeb is a high albedo station, with a surface albedo derived from GOSAT retrievals at 1.6 µm of 0.4 for the sand desert and 0.45 for the gravel plains*…

*…In Fig. R6 we show the COCCON Gobabeb station in a broader context on a global map together with the TCCON Reunion Island and Lauder stations used in this study.*

*Figure R6: Global map showing the COCCON Gobabeb, TCCON Reunion Island and Lauder sites used in this study.*

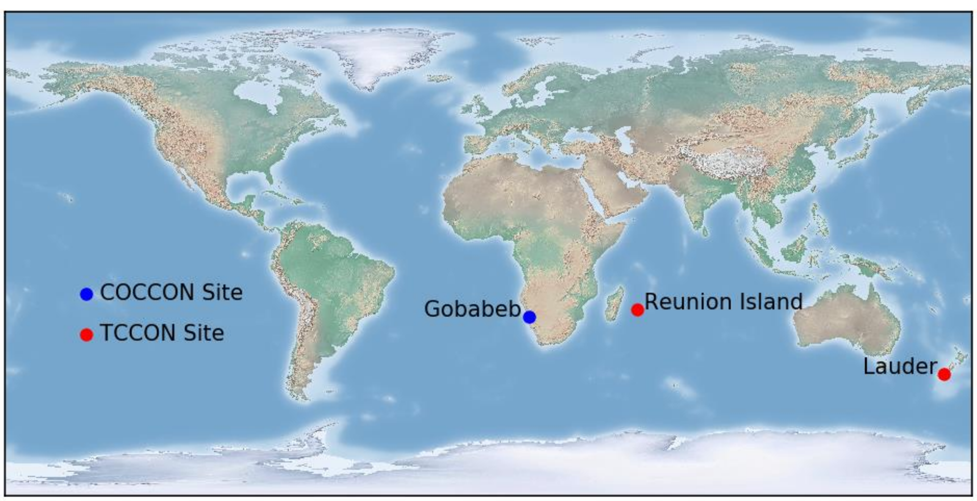



Figure 3 – Xair is not in arbitrary units - it should be mol $mol^{-1}$ or similar (or even unitless, though mol $mol^{-1}$ is more informative) as the numerator and denominator will both have units of molecules $cm^{-2}$.

Thanks. We corrected this mistake.

Several locations: data set → dataset. Same for the plural

Done

l379: put ”with different surface albedos” before ”close to”

Ok

Figure A1 appears to be missing

No, Figure A1 is at the end of the manuscript.

# 4 References

Pollard, D. F., Robinson, J., Shiona, H. and Smale, D.: Intercomparison of Total Carbon Column Observing Network (TCCON) data from two Fourier transform spectrometers at Lauder, New Zealand, Atmos. Meas. Tech., 14(2), 1501–1510, doi:10.5194/amt-14-1501-2021, 2021.