Authors' answer to the interactive comments of anonymous referee #1 on paper Heymann et al., Atmos. Meas. Tech. Discuss., 8, 1787-1832, 2015

First of all we would like to thank the referee for the helpful comments and questions. Below we give answers and clarifications to all comments and questions made by the referee.

Referee: "*Previous studies evaluated SCIAMACHY BESD XCO2 retrievals e.g. by comparison to TCCON (e.g. Reuter et al., 2010). Multiple previous studies compared GOSAT retrievals by other algorithms to TCCON (e.g. Morino et al., 2011, Butz et al., 2011, Wunch et al. 2011, . . .). Several previous studies compared and combined SCIAMACHY and/or various GOSAT XCO2 records (e.g. Oshchepkov et al., 2013, Takagi et al., 2014), including publications of the authoring team (e.g. Reuter et al., 2013, 2014).*
So, the novelty of the study is the report on how well the BESD algorithm performs for GOSAT measurements over TCCON sites. Although several other GOSAT XCO2 algorithms have been reported operational for years, the study topic could be of interest to the readers of AMT in particular if it was shown that BESD-GOSAT and BESD-SCIAMACHY are of better consistency than any other SCIAMACHY and GOSAT records. The study, in my opinion, falls short of this goal due to several serious shortcomings."

Authors: The publication presents first results from the application of the established BESD algorithm to retrieve XCO_2 from GOSAT and discusses investigations concerning the consistency between the SCIAMACHY BESD and the GOSAT BESD XCO_2 data products. This is new and has not been published before. We think that an overview about the modifications of BESD needed to retrieve XCO_2 from GOSAT and results of a detailed validation of the new GOSAT BESD data product against TCCON are especially interesting for current and future users of our product who may use our product directly or indirectly (e.g., by using the corresponding MACC product which has been generated by assimilating our GOSAT XCO_2 product). We also think that the presented investigations concerning the consistency of the satellite data products are also of interest as consistent long-term data sets of global CO_2 concentrations are required for carbon cycle research (see e.g., CEOS, 2014). We do not think that it is only of interest for the readers of AMT if it is shown that GOSAT BESD and SCIAMACHY BESD are of better consistency than any other SCIAMACHY and GOSAT records. However, we agree that comparisons with other products would be interesting but this would be a major activity and we consider this out of scope of the present study. Note also our answer to the referee's comments number 4.

Referee: "*1. The performance evaluation is limited to TCCON coincidences. Previous studies, amongst others led by the authoring team (Reuter et al., 2013), have shown that algorithm performance at TCCON sites is not necessarily representative for consistency on the global scale. BESD-SCIAMACHY and BESD-GOSAT must be compared for a globally representative ensemble to comply with the paper title.*"

Authors: We agree that it would be good to present an extended performance evaluation. We have therefore added a comparison with CarbonTracker to get additionally a more global view on the consistency of the data sets. For this purpose, two figures and the following section have been added to the manuscript:

"In addition to the comparisons with TCCON, we have also compared the BESD data sets with the model results of CarbonTracker. For this purpose, we have used data of two months in 2011: We selected May where the atmospheric CO_2 concentration in the northern hemisphere peaks and August where it reaches its minimum.

CarbonTracker is NOAA's modelling and assimilation system and has been developed to estimate global CO_2 concentrations and CO_2 surface fluxes (Peters et al., 2007). We use CarbonTracker version CT2013B downloaded from http://carbontracker.noaa.gov. Global monthly maps of GOSAT BESD, SCIAMACHY BESD and CarbonTracker XCO_2 have been generated in a grid of 5°x5°. All grid boxes with less than 15 measurements have been excluded to achieve robust results. A global mean offset has been added to GOSAT BESD (1 ppm) and SCIAMACHY BESD (0.4 ppm) to better compare the differences to CarbonTracker. From the intercomparison of the global maps the mean difference, the standard deviation of the difference and the correlation coefficient between the data sets have been computed.

Figure 6 shows the comparison results for May 2011. The GOSAT BESD, SCIAMACHY BESD and CarbonTracker maps show a similar strong latitudinal dependence of XCO_2 with high XCO_2 in the northern hemisphere and low XCO_2 in the southern hemisphere. The number of grid boxes filled with sufficient observations is larger for SCIAMACHY than for GOSAT BESD. In comparison to CarbonTracker, GOSAT BESD as well as SCIAMACHY BESD has a small mean difference (GOSAT: 0.06 ppm; SCIAMACHY: −0.18 ppm) and a similar standard deviation of the difference (~ 1.2 ppm). The correlation coefficient between the BESD data sets and CarbonTracker is similarly high (~ 0.9). The direct comparison between GOSAT BESD and SCIAMACHY BESD shows a mean difference of 0.38 ppm, a smaller standard deviation of the difference of 0.95 ppm and a similar correlation coefficient (r = 0.92) as compared to the difference to CarbonTracker.

The results for August 2011 are shown in Fig. 7. The northern hemispheric carbon uptake in this time period explains the low XCO_2 values in the northern hemisphere shown in all three datasets. The number of grid boxes is again larger for SCIAMACHY compared to GOSAT BESD. The comparison with CarbonTracker shows for SCIAMACHY a small offset (0.32 ppm). The standard deviation of the difference is somewhat smaller for GOSAT (1.06 ppm) as compared to SCIAMACHY BESD (1.32 ppm) and the correlation coefficient is high for both (GOSAT: 0.84; SCIAMACHY: 0.87). The direct comparison of the BESD data sets shows a smaller/similar standard deviation of the difference (1.06 ppm) and has a similarly high correlation coefficient (0.87) as obtained for the comparison with CarbonTracker.

We have also investigated other months of 2011 and found similar results as for May and August. The remaining differences between GOSAT and SCIAMACHY BESD are likely due to the non-perfect spatial and temporal collocations and a non-perfect BESD algorithm. However, the smaller/similar differences of the BESD data sets as compared to CarbonTracker are another indication for the high degree of consistency between GOSAT and SCIAMACHY BESD."

Referee: *"2. The above concern is even more urgent given that the paper only discusses BESD-GOSAT retrievals after a 6-parameter bias correction has been applied. To the best of my knowledge, no other GOSAT XCO2 retrieval algorithm needs that many parameters (e.g. Wunch et al., 2011, Guerlet et al., 2013). Using 6 free parameters to improve the match to TCCON and then, only discussing performance at TCCON sites appears overly optimistic. Since it is the first study on BESD-GOSAT, the study needs to document and discuss performance without bias corrections applied."*

Authors: Using a bias correction is a "state-of-the-art" technique. Takagi et al., 2014 listed all previous GOSAT algorithms and the used bias corrections (see Takagi et al.,

2014, Table 1). PPDF-S, ACOS B2.10, RemoTec v2.0 and UoI-FP v3G make use of a multivariate linear regression, the NIES v02 algorithm used only a global uniform correction. For example, Wunch et al., 2011, introduced a bias correction scheme for ACOS retrievals which depends on seven parameters, viz. blended_albedo, which has been computed from the retrieved albedo in the O_2-A band and strong CO_2 band, the difference between retrieved and ECMWF surface pressure, the airmass factor, which is computed from the solar zenith angle and the viewing zenith angle and the continuum level of the O_2-A band spectral radiance. These authors fitted the systematic differences by using five coefficents. Guerlet et al. 2013 used three parameters for the bias correction of RemoTec retrievals (α_s, SOT and z_s defining the scattering scenario of the retrieval) and fitted the systhematic errors by using three coefficients.
In our opinion, if systematic errors are identified one has to reduce these errors. Therefore, we have implemented a bias correction, which does not depend on six retrieval parameters but on five (the viewing zenith angle, the air mass factor which is computed from the solar zenith angle and the viewing zenith angle, the retrieved albedo in band one and the difference to the a priori albedo of band 2). We have fitted the known systematic difference with 7 coefficients (including an offset).
The bias corrected GOSAT BESD XCO_2 data product is the standard product used by our users. For these reasons, we decided to only present the validation results for this data product in this study.

Referee: *"3. The coincidence criterion of 10 deg x 10 deg is not very sophisticated. Various other teams have put great effort in improving coincidence criteria for satellite evaluation at TCCON sites (e.g. Wunch et al., 2011, Guerlet et al., 2013, Nguyen et al., 2014). The study should adopt one of the state-of-the-art techniques or at least, perform a sensitivity study to quantify the impact of the chosen coinicidence criterion on the reported performance."*

Authors: We have also tested other collocation criteria such as a 5° radius around a TCCON site (used also by Butz et al. 2011 and Guerlet et al. 2013) and a 350 km radius. Table S1 and S2 in the supplement show the summary statistics of the comparison of the individual data points and the daily means for all three collocation criteria (10°x10° box, 5° radius and 350 km radius). The results for all three criteria are very similar and the conclusions remain the same. As we found the largest amount of collocations using the 10°x10° box we decided to use this criterion. To clarify this in the manuscript, we have added the following paragraph to the methods part of the intercomparison section:
"We have also tested other collocation criteria such as a 5° and 350 km radius around the TCCON sites. The results of the intercomparison of the data sets using these collocation criteria have been similar to the 10°x10° box (see Tab. S1, S2 and S3 of the supplement). For the results presented here we have decided to use the 10°x10° box criterion as it provided the largest amount of collocated data points."

Referee: *"4. The study should raise the question whether combining BESD-SCIAMACHY and BESD-GOSAT is finally better than combining BESD-SCIAMACHY with any of the other GOSAT retrievals (NIES, ACOS, RemoTeC, UoL, PPDF, EMMA, . . .) e.g. for inverse modelling of surface-atmosphere CO2 exchange. Reuter et al., 2013, suggest that using ensembles of algorithms is better than using a single algorithm (with potentially persistent biases)."*

Authors: The title of our manuscript "Consistent satellite XCO_2 retrievals from SCIAMACHY and GOSAT using the BESD algorithm" does not imply that the focus of our paper is to show if the SCIAMACHY BESD and GOSAT BESD algorithm is more consistent than other GOSAT retrievals. However, we have also investigated if the GOSAT BESD XCO_2 data set is more consistent to SCIAMACHY BESD than other GOSAT data sets. For this purpose, we intercompare the validation results presented in the publication of Dils et al. (2014) with the validation results for SCIAMACHY and GOSAT BESD XCO_2.

Dils et al. (2014) validated the bias corrected GOSAT XCO_2 data sets generated by using the OCO full-physics retrieval algorithm of the University of Leicester (OCFC) and the SRON RemoTec algorithm (SRFC). They used data from April 2009 to April 2011, a collocation time of ±2 hours and all data within a 500 km radius around the TCCON sites. We use the same collocation criteria for SCIAMACHY BESD and a 5° circle around TCCON for GOSAT BESD XCO_2. The same TCCON sites have been used but we excluded Lauder due to an insufficient number of collocations. For SCIAMACHY BESD, the same time periode April 2009 to April 2011 has been used. As no GOSAT BESD XCO_2 for 2009 are currently available, we have used data from January 2010 to December 2011.

Table 1 shows the station biases of OCFC and SRFC (Dils et al., 2014) and of SCIAMACHY and GOSAT BESD. All data sets have a small offset (-0.58 – 0.15 ppm) and a similar station-to-station bias (0.47 – 0.75 ppm). In addition to these values, we have computed the correlation coefficient and the mean and the standard deviation of the difference between the station biases of all GOSAT and the SCIAMACHY BESD data sets. The mean difference shows that all three GOSAT data sets have a negative offset to SCIAMACHY BESD. Compared to the station-to-station bias of the XCO_2 data sets, the standard deviation of the difference between GOSAT BESD and SCIAMACHY BESD is smaller (0.37 ppm) and smallest compared to the difference to OCFC (0.60 ppm) and SRFC (0.79 ppm). The correlation coefficient between the station biases of SCIAMACHY BESD is large for GOSAT BESD (0.73) and small for OCFC (0.34) and SRFC (0.26). The smaller standard deviation of the difference between GOSAT BESD and SCIAMACHY BESD compared to the differences to the other GOSAT data products and the large correlation coefficient between the station biases indicate that GOSAT BESD is more consistent to SCIAMACHY BESD than other GOSAT XCO_2 data sets.

We do not include this investigation to our manuscript as we think, that the study concerning the consistency of other GOSAT data products with the SCIAMACHY BESD data product needs much more investigations. New data product versions for OCFC and SRFC are avaiable and the biases could be more consistent now. Also the NIES, PPDF and ACOS data products could be included. This investigation is a major activity and could easily provide enough stuff for an own publication.

Station	SCIA BESD Δ [ppm]	GOSAT BESD Δ [ppm]	GOSAT OCFC Δ [ppm]	GOSAT SRFC Δ [ppm]
Bialystok	0.23	-0.92	-0.52	-0.13
Bremen	-0.45	-0.55	-0.50	-0.90
Karlsruhe	-0.47	-0.64	-0.61	-1.08
Orleans	0.63	-0.29	-0.72	-0.83
Garmisch	1.11	0.44	0.31	0.32
Park Falls	0.43	0.31	-1.31	-0.77
Lamont	-0.03	-0.42	-1.04	-0.84
Darwin	-0.18	-0.81	-0.96	0.67
Wollongong	0.11	-0.46	0.15	0.88
Mean	0.15	-0.37	-0.58	-0.30
SD	0.52	0.47	0.53	0.75
Difference GOSAT – SCIA BESD				
Mean	-	0.52	0.73	0.45
SD	-	0.37	0.60	0.79
Correlation with SCIA BESD				
r [-]	1	0.73	0.34	0.26

Table 1: Station biases for SCIAMACHY (SCIA) BESD, GOSAT BESD, GOSAT OCFC and GOSAT SRFC. The station biases Δ (mean difference to TCCON) for GOSAT OCFC and GOSAT SRFC has been obtained from Dils et al., 2014. The collocation criterion for SCIA BESD is the same as used by Dils et al., 2014, 500 km around a TCCON site and ±2 hours. For GOSAT BESD, we use a 5° cirlce around a TCCON site and ±2 hours. SCIA BESD, GOSAT OCFC and GOSAT SRFC data from April 2009 - April 2011 has been used. As GOSAT BESD data from 2009 are not available, we use two years of GOSAT BESD data but from January 2010 to December 2011. "MEAN" is the mean of the station biases and "SD" the station-to-station bias computed from the standard deviation of the station biases. Also shown are the mean and standard deviation of the differences of the station biases to SCIA BESD and the correlation coefficient with SCIA BESD.

Referee: "*Section 6 and 7: The discussion of error patterns is hard to follow. Previous TCCON comparison studies highlighted the station-to-station bias deviation as the most important diagnostic since it is a measure for regionally correlated error patterns. While this measure is quoted several times in the conclusions, it does not show up in the results section nor in any table nor in the "i), ii), iii), iv)" listing on page 1802. Is "relative accuracy" the same as the station-to-station bias deviation? Are all the numbers consistent among sections 6 and 7?*"

Authors: Relative accuracy and station-to-station bias deviation means the same in our manuscript. We rework the chapters for a better readability and change "relative accuracy" to "station-to-station bias" as we want to prevent confusion.

Referee: "*Tables 5 and 6. Add columns for retrievals without bias corrections.*"

Authors: See answer to the referee comment point 2.

Referee: "*Figures 5, 6 and 8: Figures are too small and contain information mostly redundant with tables 5, 6, 7. The only new information I tend to see is that seasonal* *cylces between TCCON and BESD are different. If so, this should be discussed. If not, I suggest removing the figures.*"

Authors: We have moved Figures 5, 6 and 8 to the supplement because there are no additional information compared to the tables 5, 6 and 7.

Referee: "*Figures to be added: It would be interesting to see how the satellite-TCCON differences correlate with geophysical parameters such as used for bias correction. It would be interesting to see maps comparing BESD-SCIAMACHY and BESD-GOSAT globally.*"

Authors: Global maps comparing SCIAMACHY BESD and GOSAT BESD has been added. See answer to the referee comment point 1. Plots showing how the BESD – TCCON differences are correlated with geophysical parameters have, in our opinion, no added value as both BESD data sets make use of a bias correction which reduces correlations with these parameters.

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