

Response to the Anonymous Referee #2's comment on "Does GOSAT capture the true seasonal cycle of XCO₂?"

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We thank the Anonymous Referee #2 for their positive review of our paper and for their comments that helped us improve the paper for publication in ACP. In this letter, we respond to their comments (the original comments are shown here with *italic, blue text*) and indicate the changes made to the manuscript.

This paper explores whether GOSAT satellite observations capture the true seasonal cycle in XCO₂ in the Northern Hemisphere. GOSAT mean annual cycle amplitudes are evaluated against three versions of the "truth": TCCON, the collective wisdom of several different algorithms used to retrieve XCO₂ from GOSAT, and data assimilation products that use surface CO₂ mole fractions as constraints. The authors conclude that GOSAT captures the true amplitude to within about 1 ppm across most latitude bands, but identify a systematic offset in the XCO₂ seasonal amplitude in Europe. This may be of special interest, since a few different data assimilation and inverse modeling efforts to infer fluxes from GOSAT data have inferred a large and potentially spurious sink in Europe.

The paper is clearly written and the analysis is thorough.

The NOAA/Basu coincidence criteria seem to lead to huge footprints! Figure 2 shows the coincident observations for comparison with the Park Falls, WI TCCON site. This footprint would overlap the footprint of the TCCON site at Lamont, OK (since the latitude limit is 7.5 deg and these sites are separated by only 10 deg lat). These two sites have a seasonal that differ by several ppm, and there is a subset of ACOS data that is assumed to represent both sites. This is possibly justifiable, since transport in the free troposphere connects the two sites dynamically, but I think some justification of the criteria used, beyond a citation, is required.

Regarding the possible overlap of "footprints" of Park Falls and Lamont TCCON sites, the referee is correct that that is entirely possible. Such an overlap, however, is entirely physical; all that means is that there is a region in between the two where the XCO₂ is within 0.5 ppm of the XCO₂ at the two sites (which still allows for up to a ppm difference between the two sites). Since our collocation criterion is dynamic, such overlaps are more likely in the northern hemisphere winter, when the north-south gradient of XCO₂ over the conterminous United States is small (see examples in Figs. A and B in this response letter). During the northern hemisphere summer, when the north-south gradient is much larger and regions of constant XCO₂ are elongated zonally, such an overlap is less likely (see examples in Figs. C and D), reflecting the reality that XCO₂ at Lamont and Park Falls are different by more than a ppm. Thus, an itinerant overlap between the "footprints" of Park Falls and Lamont TCCON sites is completely consistent with the XCO₂ seasonal cycles at the two sites differing by several ppm.

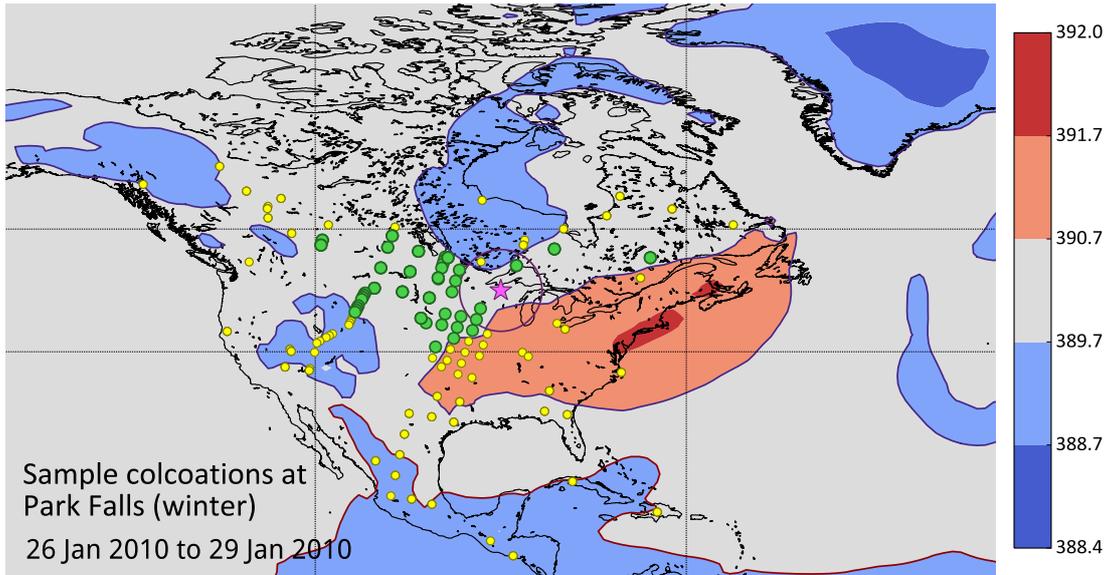


Figure A. An example of co-located GOSAT soundings in the proximity of Park Falls TCCON station (star symbol) in winter. The co-locations accepted by the NOAA/Basu technique are denoted with green symbols.

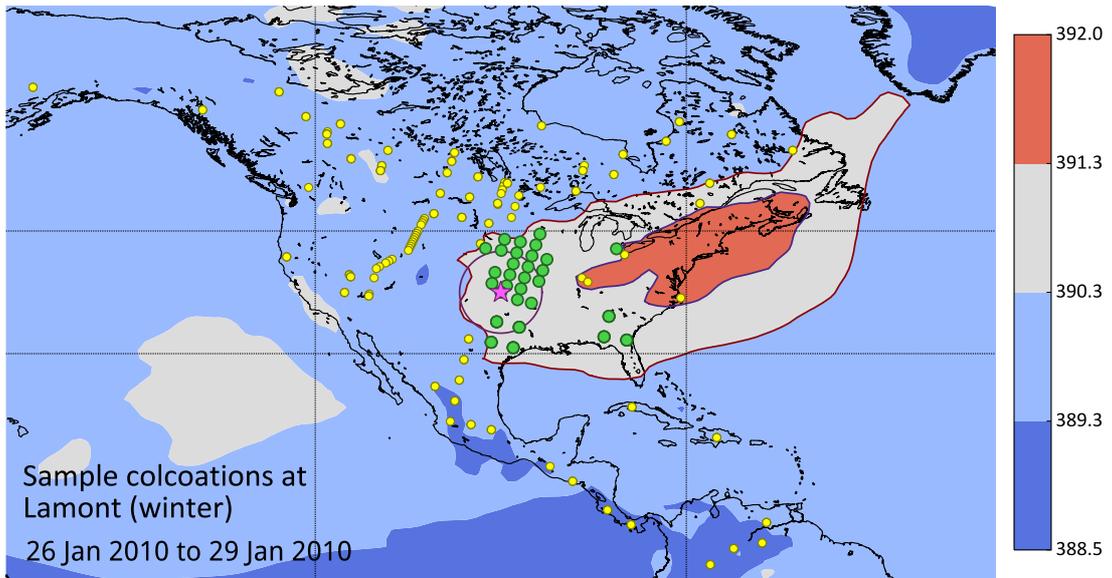


Figure B. As in Fig. A but for Lamont TCCON station.

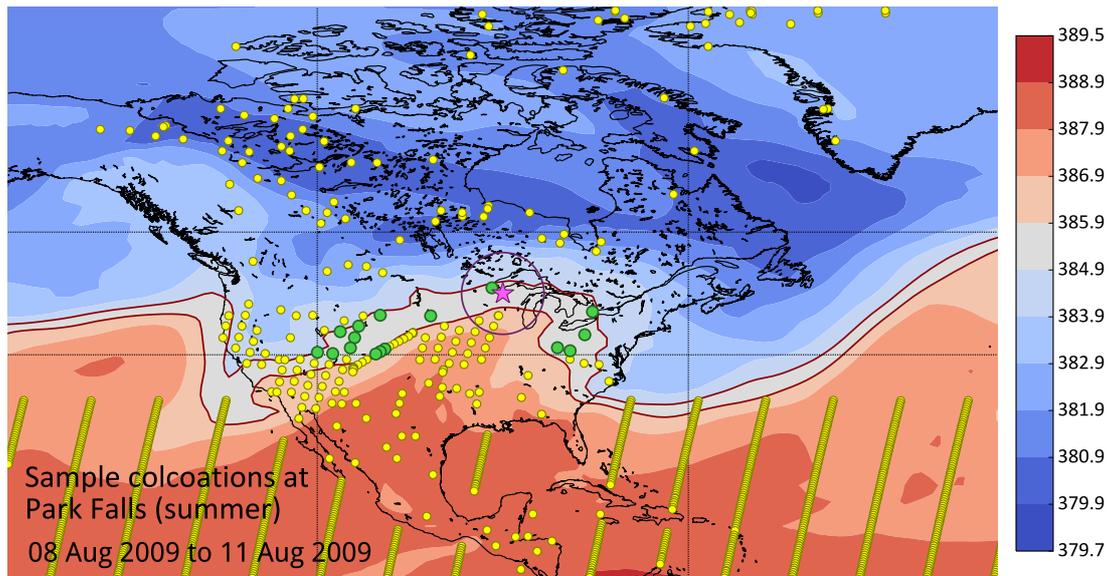


Figure C. As in Fig. A but for Park Falls station in summer.

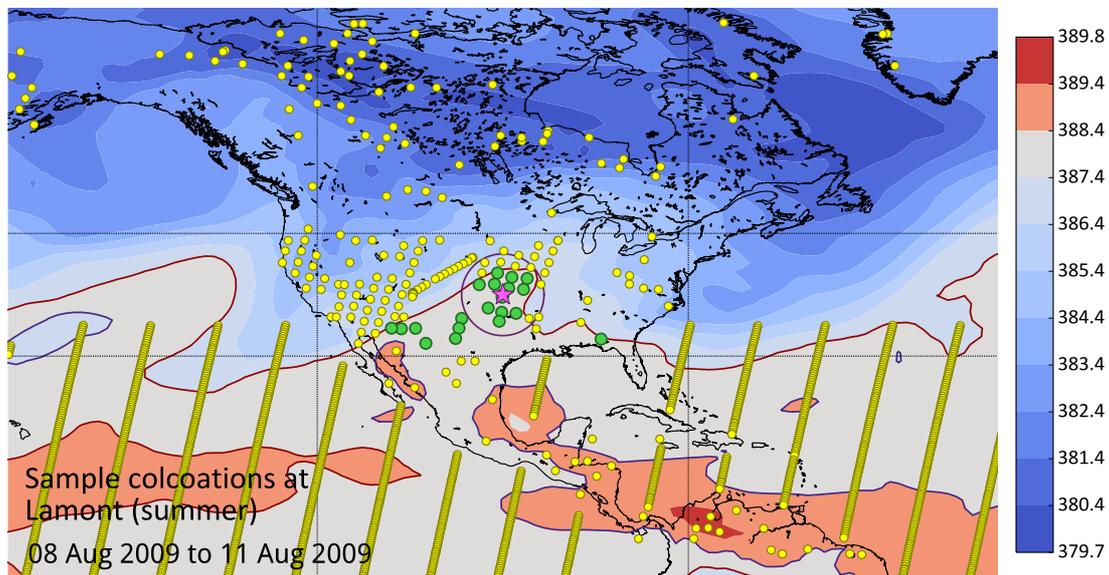


Figure D. As in Fig. A but for Lamont station in summer.

As a reaction to the referee’s comment, we have added a descriptive example figure to the paper (Fig. 2a), and clarified and expanded the text in Sect. 4.1 followingly:

“ACOS retrievals of GOSAT soundings are estimates of total column XCO_2 . Therefore, the issue of co-locating GOSAT soundings with TCCON soundings boils down to the question of whether we expect both sounding locations to have the same atmospheric XCO_2 . Any co-location technique is an assumption about the geographical region over which we expect XCO_2 to be the same as a TCCON retrieval, within some tolerance. For example, a geometrical co-location criterion, where we consider all GOSAT soundings within some fixed distance of a TCCON station, assumes that in the real atmosphere the variation of XCO_2 over that distance is smaller than said tolerance. Similarly, co-locating using the 700 hPa potential temperature (Wunch et al., 2011b) assumes that air with the same transport history – in so far as it’s reflected in the 700 hPa potential temperature

– will have the same XCO₂ (within said tolerance). However, neither of these co-location techniques account for the fact that ultimately atmospheric XCO₂ is a convolution of surface fluxes and transport. Therefore, in our paper we have applied the NOAA/Basu co-location technique (Guerlet et al., 2013a) which uses a modelled atmospheric XCO₂ field to delineate the region around a TCCON station over which we expect XCO₂ to be constant within some tolerance (0.5 ppm). Since the model is run with realistic surface fluxes and atmospheric transport, we expect this co-location technique to account for XCO₂ variations due to both. To set upper spatiotemporal limits for the co-located soundings, the GOSAT soundings were required to be within $\pm 22.5^\circ$ in longitude and $\pm 7.5^\circ$ in latitude from the TCCON site, and acquired on the same day, within 2 hours of each other. The TCCON soundings were interpolated to local noon to exclude any effects from the diurnal cycle of XCO₂. In practice, the NOAA/Basu co-location technique has several advantages: high co-location data volume, good accuracy, and good sampling of parameter space, such as surface albedo. It should also be noted that the performance of this technique does not depend on the absolute accuracy of simulated XCO₂; all that is required is for the spatial gradient of three day average XCO₂ over a few thousand kilometers to be correct to within some tolerance.

The NOAA/Basu co-location technique is visually demonstrated for the Park Falls TCCON site in Fig. 2a. All GOSAT soundings over almost five years of co-located observations at Park Falls are mapped in Fig. 2b, which shows that the exact locations of the co-located GOSAT soundings are to a minor extent dependent on the season.”

The coincidence criteria are not plotted for any European TCCON sites, which are located quite close together. It seems that the autocorrelation between the GOSAT soundings used to compute the seasonal cycle for Bialystock, Bremen, Karlsruhe, Orleans, and Garmisch would be quite high. How does this affect the significance of the bias found by the authors with respect to the seasonal cycle?

To address this, we checked the number of GOSAT soundings that are shared co-locations for all five sites in continental Europe. This number turned out to be surprisingly low: only 18 GOSAT soundings were shared by all sites (this is about 1% of all co-located soundings per site). Next, we paired up the sites to test what is the maximum number of shared soundings between two sites. The results varied between 6% and 44%. The maximum of shared soundings was between Garmisch (44%) and Karlsruhe (39%); all other combinations shared less than a third of their soundings with another site. Considering that the fractions of shared soundings were less than half for every site, the shallow seasonal cycle issue seems to exist separately for all these sites.

When attempting to explain the discrepancy between TCCON and GOSAT, the authors use TCCON retrievals from both GGG2012 and GGG2014, and note that “The difference comes likely from the extended time series and the additional measurements present in the GGG2014 version”. Please clarify what is meant here. Are an additional 1-2 years worth of data going into the second data set? Are more TCCON data used to calculate its mean annual cycle since GGG2014 is better able to

account for e.g., solar zenith angle bias so fewer observations required to be excluded? It seems that for this comparison, the authors should take the average only of the same unique soundings.

We have updated all TCCON data used in the paper to GGG2014 versions that have now become available for all stations. To avoid confusion, we removed all references to GGG2012 from the paper.

Also on p 16476, the authors write that “a shallow-biased GOSAT seasonal cycle over Europe contradicts.. a stronger carbon sink over Europe”. This is not necessarily true, since the sink only depends on the imbalance between assimilation and respiration and does not require a strong seasonal difference between these two quantities. I don’t think there is necessarily a contradiction to resolve, but I definitely don’t understand the explanatory sentence that follows referencing Reuter.

Due to the current controversy around and about the European carbon sink, and the fact that this paper does not aim to contribute directly to that discussion, we decided to remove the mention of the European carbon sink entirely.

p 16479, If there are biases unique to individual retrieval algorithms that degrade the agreement with TCCON, is it really a good idea to brush these biases under the rug and attempt to use a composite dataset that contains a regionally inconsistent set of biases (EMMA)? I don’t see the logical link that supports the use of the EMMA.

During the revision, we tested the performance of EMMA and have modified this part in the text followingly: “Since none of the retrieval algorithms clearly outperformed the others at every TCCON site, we repeated the analysis for the ensemble median algorithm EMMA (Reuter et al., 2013), which combines all individual retrievals into one data set of median XCO₂ values. Even though EMMA had the smallest RMS error at four TCCON sites overall, it did not perform systematically better or worse than the individual retrieval algorithms in capturing the seasonal cycle of XCO₂.”

p 16483, The authors discuss the role of prior fluxes as driving differences in the GOSAT-to-model comparison, but should also include discussion of the differences in the transport models at the heart of each inversion.

The role of transport models (and the need of further studies on the matter) is already mentioned in several parts in the text (in particular in Sect. 5.3), and because this paper is focused on the validation of the seasonality of satellite-retrieved XCO₂, we do not wish to expand our speculation about the models further without additional results.

Figures: Figure 4: This is the closest to raw data that we see for most of the sites, so I would like it if this figure were bigger so the reader could interpret it better. Maybe two columns, but the same height so that the tick marks could be better spaced and labeled?

We updated the figure following these suggestions. In the updated version, the

seasonal cycles and especially the differences between TCCON and ACOS stand out more, which is good. We also added in dashed lines for the unobserved times of year.

Figure 8 and discussion in the text of longitude-dependence of seasonal cycle: It would be nice if there were a figure in the paper that showed the position of the continents and some indicator of the dominant tropospheric transport pattern to allow the reader to better interpret. For example, is the relatively higher amplitude between 120-60W due to the fact that those measurements are made over a continent? Or is it due to the fact that the jet is northwesterly at this location?

We added a small map of the Northern Hemisphere to the top of the figure, and highlighted the region in question. From this map, the locations of the continents with respect to the latitude-longitude regions can be conveniently seen. We also added this sentence to the text: "The increased seasonal cycle is likely due to the large seasonal sink of the boreal forests, accrued in the total column as the observation point is moved eastward."

wording: Abstract: "The seasonal cycle ... represents an important variable to accurately measure from space", but we can't measure the seasonal cycle since the long-term upward trend necessitates pre-treatment of the measurements. Therefore, the wording might be better as "represents an important quantity to test the accuracy of measurements from space" or something like that.

Modified as suggested.

"GOSAT agrees with the models". Why should the data have to agree with models? Perhaps better worded as "models are consistent with the GOSAT amplitude to within 1.4 ppm"

Corrected as suggested.

p 16465 "This finding not only suggests that regional XCO₂ can be indicative of local fluxes". I find this wording confusing.

We modified the sentence as follows: "This finding suggests that regional XCO₂ seasonal cycles may be indicative of local fluxes, and hence that satellite-measured XCO₂ may be useful in evaluating model fidelity without resorting to full carbon flux inversions. It is also another reminder that there may be much to be gained by assimilating space-based XCO₂ retrievals which vastly expand the current in-situ measurement network; a lesson shown previously by a number of studies (e.g., Rayner and O'Brien, 2001; Chevallier et al., 2007; Takagi et al., 2011, 2014; Maksuytov et al., 2013)."

p 16467 "GOSAT measures scattered solar". I think "reflected" sunlight is more accurate term.

Corrected as suggested.