Dear Editor,

According to the reviewers' comments and suggestions, we have made major revision to our manuscript. The main changes in the manuscript are as follows:

1) As suggested by one reviewer, we add two new inversion experiments, one using surface observations and another using global CO_2 trend.

2) To further investigate the difference of posterior flux from GOSAT and OCO-2 inversions, we add evaluations of two satellite XCO_2 retrievals against TCCON XCO_2 retrievals and the analysis of mismatches from two inversions.

3) As suggested by two reviewers, we have changed the title to "Terrestrial ecosystem carbon fluxes estimated using GOSAT and OCO-2 XCO_2 retrievals.

4) In Section3, we add three sub-sections to describe inversion setting of satellite data based, in-situ measurements and benchmark inversions, respectively.

5) We rewrite the most part of the Section 4. We update all the subsections with results from two new inversions. We add more analysis and discussions on probable reasons for the differences of inverted carbon fluxes between the two satellite-based inversions. We update Table 1and 2 with results from two added inversions; we redraw the Figure 4 to add results from in situ and benchmark inversions; we update Table 2 with results from two new inversions; we add statistics of model-data mismatches into Table 3; we add Table 4 to presents the comparison results of satellite retrievals against TCCON retrievals; we replace Figure 6 and 8 in the old manuscript with Table 6 to present the updated evaluation results using both flask observations and TCCON retrievals; we redraw the Figure 9 in the old version of manuscript and rename it as Figure 7 to present the biases of posterior XCO_2 from four inversions at 13 TCCON sites.

6) In Section 5, based on the new results and analysis, we rewrite this whole section to summarize our findings and give our revised conclusions.

The point-by-point response to the reviews and the detailed changes are listed in the attachments. Many thanks to you and the referees for the time and effort you expend on this paper.

Best Regards,

Sincerely yours,

Fei Jiang

Referee #1:

We would like to thank the anonymous referee for his/her comprehensive review and valuable suggestions. These suggestions help us to present our results more clearly. In response, we have made changes according to the referee's suggestions and replied to all comments point by point. All the page and line number for corrections are referred to the revised manuscript, while the page and line number from original reviews are kept intact.

Referee: General comments. The authors make contribution to an under-explored topic of understanding differences between the global fluxes estimates based on GOSAT and OCO-2 satellite observations of atmospheric carbon dioxide. By applying same inverse modeling system, same prior fluxes and inverse modeling setup, and using retrievals made with a very similar algorithm, they constructed a good base for comparing performance of the GOSAT and OCO-2 data in application to a problem of quantifying regional carbon fluxes. The study has a potential to contribute to an important problem of understanding the global carbon cycle response to 2015 El-Nino climate anomaly, by providing the alternative views to the phenomenon from the 3 independent observing systems. Although most of important work is already done in this study, more analysis and possibly more extra model runs are required to arrive at robust conclusions, as there is still inconsistency between global annual terrestrial flux estimates made with different observing systems, that should be addressed and elaborated. The study should benefit from giving authors extra time for making necessary revisions.

Response: We appreciate the referee's suggestion on conducting more model runs and addressing the inconsistency between global annual terrestrial flux estimates from different observing systems. During this revision, we have run two more inversions based on the comments from another referee. In the revised manuscript, in order to make the comparison between satellites based inversions and in situ observations based inversion more consistent, we remove the comparison with CT2016 results, and conduct an inversion using in situ measurements so that we don't have to deal with the differences in transport models and inversion settings between this study and CT2016, which might compound the comparisons. We also conduct a poor man's inversion to a benchmark (Chevalier et al., 2009), against which more robust evaluation of posterior flux from other three inversions can be made.

To investigate the inconsistency between global annual terrestrial flux estimates from different observing systems, we add evaluations for the satellite XCO2 retrievals using TCCON retrievals and simulated CO_2 field as a reference. We found that even with bias-correction applied, both GOSAT and OCO-2 XCO2 retrievals still have relatively large biases. The distinctive differences between GOSAT and OCO-2 data could result in quite different annual global terrestrial land flux estimates.

We have updated the manuscript with new experiments results and more detailed analysis in the revised paper.

Specific comments.

Line 1: Title can be simplified to "Terrestrial ecosystem carbon fluxes estimated using GOSAT and OCO-2 retrievals."

Response: Thanks for this suggestion. The title has been simplified to the suggested one. See lines 1-2 in the revised manuscript.

Line 66: OCO-2 observations have lower random noise compared to GOSAT, but it is not related to vertical difference in sensitivity. Generally, SWIR observations by both sensors have flat sensitivity to CO_2 from the surface to the upper troposphere, thus citing sizable difference between GOSAT and OCO-2 in sensitivity to lower troposphere concentrations requires elaboration, giving more details. Suggest to replace "higher sensitivity near the surface" by "higher sensitivity to column CO2".

Response: Many thanks for this suggestion. "higher sensitivity near the surface" has been replaced by "higher sensitivity to column CO_2" as suggested. See line 66 of the revised manuscript.

Line 171: It is useful to elaborate on application of scaling factors to carbon flux – are those factors applied to total carbon flux in each grid or separately by each optimized component.

Response: We have added "The scaling factors are applied to each carbon flux components to be optimized monthly in each model grid point." in the first paragraph of Section 2.3.3. See lines 175-176 of the revised manuscript.

Line 237-240: The differences between net flux for 2015 should be related to different atmospheric CO2 growth rate between ground based (also used used in CT2016), GOSAT and OCO-2 observations. Suggest to add those atmospheric CO2 growth rate estimates to comparison, along with inversion-optimized posterior growth rate for all experiments. If the difference between observed ground-based, GOSAT and OCO-2 growth rates is not as much as appears in the inversion results, the inversion setup should be adjusted to provide sufficient constraint on fluxes, so that the growth rate in the inversion optimized simulation matches the observed growth rate.

Response: The differences of net flux are indeed related to the different atmospheric CO_2 growth rate between different observing system. However, as shown by Figure 1 in the manuscript, satellite retrievals are unevenly distributed spatially and temporally, which makes it difficult to estimate global atmospheric CO_2 growth rate accurately. We have evaluated the uncertainties of the two satellite retrievals using TCCON retrievals, which might better explain the differences of inverted net flux.

For details, please refer to Lines 379 to 392, pages 20-21 in the revised manuscript.

Technical corrections

Line 26: Suggest to spell out CT2016 as Carbontracker 2016.

Response: As suggested by another referee, to make the comparisons between different observing systems more consistent, we have replaced CT2016 results with estimates from in-situ observations using our inversion method.

Line 43: Need to add "et al." to Chevallier 2007

Response: We have added "et al." to that reference. See line 44 in the revised manuscript.

Line 54: Note that in Takagi et al 2011 only flux uncertainty and uncertainty reduction are estimated, not the fluxes themselves.

Response: Thanks. We have removed "Takagi et al., 2011" from the reference. See line 55 in the revised manuscript.

Line 82: Reference to GEOS-Chem adjoint is needed here.

Response: The reference "Henze et al., 2007" has been added. See line 82 in the revised manuscript.

Line 105: Replace "Before used" to "Before being used" or "Before using"

Response: We have changed "Before used" to "Before being used". See lines 106-107, page 5 in the revised manuscript.

Line 212: Add period in Single et al, 2011

Response: We have done the revision. See line 214 of the revised manuscript

Line 219: Uncertainty is assigned to ocean flux, while it was stated that only terrestrial fluxes are not optimized on

Response: Actually, ocean flux has also been optimized in our inversions. We have added "Both terrestrial ecosystem CO_2 exchanges and ocean flux are optimized in our inversions" in Lines 211-212 of the revised manuscript.

Line 209-210: Need to make the text consistent.

Response: Yes, we have made it consistent. we have added "Both terrestrial ecosystem CO_2 exchanges and ocean flux are optimized in our inversions" in Lines 211-212 of the revised manuscript.

Line 256: Change 'priori' to 'prior' here and further in the text.

Response: Thanks for pointing out this error. We have checked the manuscript and changed all inappropriate "priori" to "prior".

Line 275: Reference is missing.

Response: The missing reference “Gurney et al., 2002” has been added. See line 293, page 14 in the revised manuscript.

Line 523: Suggest correcting “Bron” to “Breon”

Response: We have corrected “Bron” to “Breon”. See line 538, page 27 in the revised manuscript.

Reference:

Chevallier, F., et al. (2010), CO2 surface fluxes at grid point scale estimated from a global 21 year reanalysis of atmospheric measurements, J. Geophys. Res., 115, D21307, doi:10.1029/2010JD013887.

Referee #2:

We would like to thank the anonymous referee #2 for his/her comprehensive review and valuable suggestions. These suggestions help us to present our results more clearly. In response, we have made changes according to the referee's suggestions and replied to all comments point by point. All the page and line number for corrections are referred to the revised manuscript, while the page and line number from original reviews are kept intact.

Referee: This manuscript presents the results from a numerical experiment in which two inverse estimates of land carbon uptake were made, driven by two different satellite retrievals. One of them results from OCO-2 spectra, while the other one comes from GOSAT. The inverse system is based on GEOS-CHEM and a 4D-VAR method, and spans the year 2015 completely. Posterior fluxes are evaluated by comparing against CT2016 fluxes, and against a set of flask observations, as well as TCCON XCO2 retrievals. The authors conclude that the inversion brings fluxes in closer agreement with all three of these, and differences between the two flux estimates are discussed in the text. Overall, the manuscript is easy to read and organized logically, and sufficient information is presented to allow the reader to appreciate the results.

What is missing from the current manuscript mostly is scientific depth. The experiment conducted is relatively straightforward, and the text at many points falls into long repetitions of numbers presented already in figures and tables. The differences are highlighted, but what drives these differences, what they imply for the use of these satellite data, and what to learn from the comparisons remains unclear. This does not invalidate the substantial effort, but it brings into question whether a publication like this should be considered scientific literature, or a technical report. I will leave this for the editor to judge.

But even for a technical report, I find the manuscript as presented currently incomplete. The demonstration of smaller biases relative to TCCON and flask observations, and the incidental agreement with CT2016, or GCP, or a set of Asian inversions, brings me to hypothesize that the improvements are not due to the use of the spatially explicit satellite data, but simply a manifestation of a better global total land sink compared to the prior. This can be tested using the poor-man's-inversion first described by Chevallier et al., (2010), in which a global residual land sink (for example that from GCP) is projected onto the land biosphere following the pattern of Net Primary Production. This benchmark is more difficult to beat than a prior from CT2016, as it inherently is globally unbiased and follows patterns of vegetation activity. Improvements beyond those in a poor-man's-inversion due to the use of satellite data would imply that spatial patterns can indeed be estimated from such satellite data, and thus make this manuscript worth reading. Finally, the use of CT2016 as benchmark for a non-satellite inversion seems illogical to me, and should be replaced by a flask-only inversion using the same system as used for the other inversions.

Without these two additions, I feel that this manuscript is not ready for publication in ACP, either as a technical report or as a scientific paper. A long list of further remarks, and points that require further explanation and discussion comes inside the annotated PDF that accompanies this review.

Response: We accept the referee's comments on the lack of in depth analysis and discussions of the two satellite based inversions in the older manuscript. We are grateful to the referee for suggesting the addition of one inversion using surface observations and another benchmark inversion using global CO_2 trend as baseline, which are instrumental in improving our manuscript to its current level. During the revision, we add two inversions as suggested. An evaluation for the two satellite XCO_2 retrievals against TCCON XCO_2 retrievals and an examination of mismatches from both GOSAT and OCO-2 inversions are performed to better understand the uncertainties of the two satellite retrievals. We add more discussions on probable reasons for the differences of inverted carbon fluxes between the two satellite-based inversions. We have updated the manuscript with new inversion results, rewritten the conclusions and made the necessary modifications accordingly.

Main changes in the revised manuscripts: In Section 3, we add subsection 3.1

Inversions using satellite XCO_2 retrievals (see Lines 225-231) to describe two satellite-based inversions; subsection 3.2 Inversion using in situ measurements (see Lines 232-241) to describe in situ inversion setting; subsection 3.3 Benchmark inversion (see Lines 242-258) to describe poor man's inversion setting.

In section 4, we rewrite the whole subsection 4.1 (see Lines 260-272) to discuss the global carbon flux updated with results from two added inversions. We also update Table 1 (see Lines 273-275) with results from in situ and benchmark inversions.

In section 4.2, we rephrase the comparison between inverted regional carbon flux from OCO-2 and GOSAT inversions (see Lines 291-312); we added the comparisons of inverted regional flux between all four inversions (see Lines 319-326); we reorganize the discussion on the relationship between the changes of fluxes and satellite data amount for GOSAT and OCO-2 inversions (see Lines 327-352)； we redraw the Figure 4 (see Lines 313-315) to add results from in situ and benchmark inversions; we update Table 2 (see Lines 316-317) with results from two new inversions; we add analysis of model-data mismatches from two satellite data based inversions and the discussion on the difference of mismatches being the possible reason for the differences in the inverted flux (see Lines 363-377); we add an evaluation of satellite retrievals against TCCON retrievals and discussions for the impact of uncertainties of satellite retrievals on the inversions (see Lines 379-392); we add statistics of model-data mismatches from GOSAT and OCO-2 inversions into Table 3 (see Lines 354-357); and we add Table 4 (see Lines 392-393), which presents the comparison results of satellite retrievals against TCCON retrievals.

In section 4.3.1 Flask observations (see Lines 394-430), with the addition of the two new inversions and different flask observation dataset adopted, to present new evaluation results, we rewrite this whole subsection to show the uncertainties of posterior mixing ratios from 4 inversions and to discuss the improvement of posterior flux by different inversions; we replace Figure 6 and 8 in the old manuscript with Table 6 (see Lines 464-466) to present the evaluation results using both flask observations and TCCON retrievals; we rewrite the most part of subsection 4.3.2 TCCON observations (see Lines 435-463) to update the evaluation results and give a more detailed discussion on the improvement of posterior XCO_2 by four inversions than the old version of manuscript; we redraw the Figure 9 in the old version of manuscript and rename it as Figure 7 (see Lines 466-468) to present the biases of posterior XCO_2 from four inversions at 13 TCCON sites.

In Section 5 Summary and Conclusions (see Lines 471-498): based on the results and analysis, we rewrite this whole section to summarize our findings and give our revised conclusions.

Line 1: This title is not very accessible to a wider public, who likely will not know what an "inverted terrestrial ecosystem carbon flux" is.

Response: Thank you for this comment. As suggested by referee #1, we have changed the title to “Terrestrial ecosystem carbon fluxes estimated using GOSAT and OCO-2 XCO_2 retrievals.”

Line 11: Please mention right away the retrieval versions used, as this has a huge impact on inversion results.

Response: We have added the retrieval versions of “Version b7.3” (see Line 13 and 105)

Line 20-21: Given that the total is larger, this would be quite obvious

Response: A stronger total global land sink from GOSAT inversion doesn’t necessarily means that carbon sink of most regions are stronger than carbon sink of corresponding regions estimated from OCO-2 inversion. For instance, several regions with very large carbon sink might dominate the global total, even with weak carbon sink or weak source in several regions, we may still have a very large global total sink. So this sentence “Regionally, in most regions, the land sinks inferred from GOSAT data are also stronger than those from OCO-2 data.” is meaning and we keep it in the manuscript (see Lines 22-23).

Line 24: increased and decreased relative to the prior fluxes, which makes it important to know what these are to appreciate the sentence

Response: This sentence is not well organized and causes ambiguity. We have revised this sentence to **“**In temperate regions, the prior land sinks are significantly increased, while in tropical regions the prior land sinks are decreased.” (see Lines 25-26)

Line 24: it is hard to see how a conclusion on carbon fluxes can be drawn based on atmospheric CO_2 columns and flasks. To believe the qualification "improved" I would need to see an independent comparison to fluxes. Also here, the term "improved" asks for a statement on what the baseline was that you compared to

Response: We agree with the referee that it is hard to draw conclusion on flux based CO_2 observations. It is an indirect way to evaluate the quality of inverted flux. However, with the lack of direct measurements of flux, there are not much options. Therefore, we follow referee’s suggestions to run in situ and benchmark inversions and the comparison with these two inversions can help us to evaluate the quality of inverted flux in satellite-based inversions. We have revised the last sentence of the abstract to “Evaluations using flask and TCCON observations and the comparisons with in situ and benchmark inversions suggest that GOSAT data, can effectively improve the carbon flux estimates in the northern hemisphere.” (see Lines 29-31)

Line 41: It is important to stress that these studies were all theoretical, and made many assumptions on the errors and their structure to show the potential of satellite observations. Studies done since then using actual retrieved XCO2 have not confirmed the idea that fluxes can be improved (yet)

Response: Thanks for referee for pointing out this. We have revised the sentence to “Studies have shown that, theoretically, satellite observations, though with lower precision than in-situ measurements, can improve the carbon flux estimates”. (see Lines 42-43)

Line 45: This description is incorrect: these sensors can sense light at wavelengths affected by atmospheric mixing ratios of CO_2, but they never measure concentrations.

Response: Yes, you are right. We have replaced "measure" with "retrieve**"** (see Line 46).

Line 64: I would not say that the community is looking for consensus. Efforts are underway to determine the true fluxes through more direct measurements at the surface.

Response: We agree with the referee's comment. We have revised that sentence to "efforts to improve the accuracy of Europe carbon sink estimate are still ongoing**".** (see Lines 64-65)

Line 75: I am not sure that this is a question of interest to the community. The qualification of which one is better will not drive ongoing work on satellite-based inversions, it is the availability of different datasets over different time periods. In the end, we will use anything that helps us understand the carbon cycle better, and we will discard everything that does not.

Response: We agree with the referee that the availability of different datasets over different time periods is important. Nonetheless, before we put all those datasets into one inversion system, we need to know the merits and demerits of every dataset relative to each other. For instance, as added in the revised manuscript, compared with the GOSAT retrievals, OCO-2 retrievals exhibit a relative large positive bias and consequently, give rise to weak posterior land sink. Thus, when we perform the synergy use of two satellite retrievals to constraint carbon flux, the large bias of one satellite retrievals will degrade the improvement by another satellite retrievals with small biases.

Line 81: Abstract said July 2014, please check

Response: We have made the correction in the abstract. It is "Oct, 2014" (see Line 81).

Line 81: to = through

Response: We have changed “to” to “through” (see Line 81).

Line 83-84: Delete “We analyze the differences of inverted terrestrial ecosystem carbon flux between using two XCO_2 data.”

Response: We have deleted that sentence**.** (see Line 83)

Line 119: Please note here the near lack of any data >60N, which would cover the Boreal regions that are later discussed

Response: We have added sentence “Due to the cloud contamination, there are few retrievals in a large portion of tropical land. In northern high latitude area, especially in boreal regions, due to the low soar zenith angle, available satellite retrievals are very sparse.” into Section 2.1 to describe the lack of data in northern high latitude.” (see Lines 122-124)

Line 131: This suggests many more were available but you decided to limit it to 47? Why??

Response: Thank you for this question. Using “chosen” might cause confusion here. Actually, at the time of doing experiment, we downloaded all available dataset from World Data Center for Greenhouse Gases (WDCGG) website. We picked out all flask sites. There were only 47 flask sites with available observations over the year of 2015. Now that we added inversion using in-situ data from Obspack, we replaced flask observations from WDCGG with those from Obspack. We got 56 flask sites with valid observations for 2015. However, there are 4 sites, namely, HUN, HPB, SGP, and TAP, where the standard deviations of first guess mismatch are greater than 5 ppm. So we wouldn’t use those 4 sites for evaluation and end up with 52 flask sites. We have updated the relevant text on using flask observations in the manuscript. (see Lines 129-137, 395-405)

Line 143: Is this part of the products you downloaded? If so, then there is no need to mention it here. If not, how was the bias correction done by your team?

Response: Yes, it is part of the products we downloaded. In addition, this sentence doesn’t provide much information and is repetition of statement made elsewhere. We have deleted that sentence. (see Lines 151-152)

Line 173: Is this term part of the summation?? Please add extra brackets if not

Response: It is not part of the summation. We have added extra brackets in the equation. $J(\mathrm{c}) = \frac{1}{2}\sum_{i=1}^{N}\left(XCO_{2,i}^{m} - XCO_{2,i}^{obs}\right)S_{obs,i}^{-1}\left(XCO_{2,i}^{m} - XCO_{2,i}^{obs}\right) + \left(\frac{1}{2}(c - c_a)S_c^{-1}(c - c_a)\right)$(see Line 178)

Line 186-187: These come from the ACOS data product I presume?

Response: Yes. We have added the sentence “These last four quantities are provided from ACOS Version 7.3 Level 2 Lite products.” (see Lines 192-193) to give the origin of products.

Line 193, 200,202,203,205,206: I am confused about the fossil fuel fluxes you used. There is a reference to CDIAC here, but it also says that you used the CT2016 fluxes, which according to their website are not the same as CDIAC. Finally, you mention a number of other sources of FF-CO_2 from shipping, airplanes, and oxidation. Your tables however simply quote the CT2016 totals it seems. So what was done??

Response: Yes, the fossil fuel fluxes from CT2016 is not the same as CDIAC, but the average of CDIAC and ODIAC products. We have made the correction in the revised manuscript (Lines 202-205). GEOS-Chem CO_2 emission module added shipping emission since that part is not included in the CIDAC product. Aviation and oxidation are still part of total fossil fuel emission from CIDAC. GEOS-Chem just deducts from the CIDAC the part of aviation and oxidation and spread them into the level they should be released. Thus the total fossil fuel emission is still kept the same as prescribed.

Line 209: A citation or other proof is needed. I actually have not so much faith in these fluxes compared to more pCO2 driven estimates such as from Rodenbeck.

Response: Yes, it is inappropriate to state that optimized ocean flux from CT2016 represents a more realistic state of ocean flux. However, in this study, first, we focus on the inversion of terrestrial carbon flux. Second, for all four inversion experiments, we use the same ocean flux. Therefore, the choice of ocean flux should not have much impact on the issues we are investigating in this study. We have rewritten the description of the prior flux in the manuscript. (see Lines 209-210)

Line 214: What are the number of degrees of freedom in the matrices? Likely to be less than a few hundred

Response: For one month, the number of degrees of freedom is around 470.

Line 217: Please justify this choice, and the difference between lat and lon scales. To me these scales seem very long given the large data density inherent to a satellite inversion. Why can this not be smaller? What would be the effect on the inversion?

Response: The difference between latitude and longitude are just for convenience of applying off-diagonal covariance matrix, which is difficult to provide in the GEOS-Chem adjoint model efficiently (Single et al., 2011). The scale length of 500 km is similar to what Chevallier et al. (2010) has used in their study. Though satellite retrievals have better spatial coverage than in-situ measurements, they are not dense enough and not evenly distributed. For instance, there are a few thousand retrievals per month in temperate regions but very sparse retrievals in northern high latitude and tropical regions for assimilation. The longer scale length should extend constraints over regions which are not well sampled by satellites.

Line 220-222: I do not understand this sentence. What are the five and three numbers quoted?

Response: The three and five are errors of scaling factors for land and ocean flux respectively. We have corrected that sentence as "the uncertainty of scaling factor for the prior land and ocean fluxes in each month at the grid cell level are assigned to 3 and 5,” (see Lines 223-224).

Line 225: I do not see how this procedure accounts for correlated errors in the grid-based retrievals?

Response: Satellite XCO_2 retrievals are pixel values at instrument viewing resolution and are not grid-based retrievals. Within the model cell box with the size of 2.5x2 degree, there are many pixels which are correlated to some extent. The averaging of those pixels should account for correlated errors.

Line 231: Why did you not also perform an inversion against the surface network data only, to complement the satellite based effort? Now you need to compare your fluxes against CT2016 all the time, when you could have simply created your own. Then you also would not have had to deal with the difference in transport models that now confounds the comparison.

Response: We have performed an inversion using surface network data and need not to compare against CT2016. A subsection is added to describe in situ inversion setting in the revised manuscript. (see Lines 233-241)

Line 254: The CT2016 website suggests that this number should be -2.62 PgC/yr. What creates the difference?

Response: We have noticed the difference between what we got and the number from CT2016 website. We checked our calculation very carefully. Since we run GEOS-Chem model at a resolution of 2.5x2 degree, we regridded the CT2016 carbon flux at 1x1 degree resolution into our model resolution. The global totals are computed from carbon fluxes at 2.5x2 degree resolution. The regridding procedure we used might cause the difference of our number from CT2016 value. Since we have removed the CT2016 results from our comparison in the revised manuscript (see Lines 274-275), we don’t need recheck the calculation again.

Line 254: The CT2016 website has this as 5.51 PgC/yr it seems...?

Response: The same reason as mentioned above. (see Lines 274-275)

Line 254: It is difficult to compare atmospheric growth rates directly with flux conversions, as the assumption of instantaneous mixing is that one makes is likely to be false at such short time scales. Please mention this in the text, because now the number of 6.23 looks "better" while it is simply a different metric (that happens to be close to the XCO2 based estimates).

Response: Now that we have conducted benchmark inversion, we can use benchmark result as a standard and have removed GCP estimate in the revised paper. (see Lines 274-275)

Line 275: Lack references

Response: We have added the missing reference "Gurney et al., 2002". (see Line 293)

Line 278-321: Starting from here, the text becomes a very long description of the numbers that are summarized already in the Table. The words written here do not add anything to add, and the numbers provided are simply copies of the information that is displayed. It can be removed fully from line 278 through line 321.

Response: We agree with referee that the description is rather long. However, detailed comparison of regional flux is important for us to understand the impact of satellite retrievals on inversions. Just checking the values in those tables might not be enough. So we will keep the description of comparison and have made this long description more concise. (see Lines 291-312)

Line 322: delete "basically"

Response: We have deleted it. (see Line 335)

Line 324: This sounds like an interesting observation: changes in fluxes are largest there where the coverage is least?!

Response: What we want to point out is that the changes in fluxes are largest there where the coverage is the best. The region with least coverage is Northern Boreal Land where the inverted flux has the smallest change relative to the prior flux. (see Lines 334-337)

Line 333: changed from the prior you mean, or do you mean different between two inversions?

Response: We mean more carbon flux is changed relative to the prior. We have added "relative to the prior flux" to that sentence. (see Line 346)

Line 340: This sounds quite speculative, yet the statement is also quite obvious. The challenge is to quantify, through your experiments, what the sensitivity to sensor accuracy and spatial resolution is.

Response: We agree with the referee that this statement is speculative and obvious. However, based the results we have from our experiments, we are unable to draw any conclusions on the sensitivity to sensor accuracy and the spatial resolution of those two sensors. Thus we have deleted this statement in the revised manuscript. (see Lines 351-352)

Line 343: delete "basically"

Response: We have removed the paragraph containing "basically" as pointed out in the first response "**Main changes in the revised manuscripts**".

Line344: delete "CT2016"

Response: We have removed the paragraph containing "CT2016" in the section presenting comparison between inversions as pointed out in the paragraphs of "**Main changes in the revised manuscripts**" in the first response.

Line 350: In my opinion this debate is not so intense lately, and the community overall does not believe the large sink to be realistic. And instead of simply remarking on it, your framework could be used to shed some more light on the situation. This would require a flask-based inversion to compare the two satellite-based ones again though.

Response: We have performed an in-situ observation-based inversion to compare with our results using satellite retrievals. The carbon sink in Europe estimated from in-situ inversion is close to the estimates from the two satellite inversions. We are still working on the discrepancy of Europe carbon estimate between our in-situ inversion and other in-situ based inversions. In the manuscript, since we have removed CT2016 results related comparison. Thus, most part of this section is rewritten as listed in "**Main changes in the revised manuscripts**".

Line 364: probably better to use "suggest", as there is no conclusion possible based on this evidence discussed.

Response: The paragraph using "indicate" has been rewritten.

Line 389: What is quite interesting to discuss is the difference in global land uptake: the total would suggest quite different global growth rates in atmospheric CO_2, a metric that we know quite well.

Response: We have added more discussions on the difference of different global land uptake estimate. (see Lines 260-276)

Line 408: The fact that these do not improve suggests that it is mostly the new global balance that is improved in the inversions. Hence my request for a benchmark against a poor man's inversion

Response: After we conducted in situ inversion and benchmark inversion, we redid the evaluation using flask observations from ObsPack product and found that the little improvement in standard deviations are mainly due to the use of 4 sites, namely, HPA, HUN, SGP and TAP, since our transport model is unable to capture the CO_2 levels and variations of these 4 sites. At these 4 sites, the standard deviations of mismatch are larger than 5 ppm. So we exclude these 4 sites from our evaluation. The updated result show improvement in the reduction of both bias and standard deviation. In addition, the addition of benchmark inversion did allow us to better evaluate our satellite data based inversions. We have updated the relevant text in the revised manuscript (see Lines 395-410).

Line 419: For a bias, this is quite large.

Response: Yes, we agree with the referee that it is a quite large bias. In the updated manuscript, we have revised the statement and pointed out that the limited improvement is made by OCO-2 retrievals. (see Lines 436-466)

Line 422-423: I am not sure if the evidence agrees with the conclusion presented. First of all, the evidence concerns mixing ratio biases while the conclusion is on fluxes. Second, the reduction of the bias could just as easily have been obtained in the simple "null experiment" that I proposed earlier: take the global growth rate, subtract 2 PgC/yr of ocean fluxes, and spread the remaining flux across the vegetated land weighted by NPP. That land flux transported should be the baseline to beat for an inversion (not the prior flux). See Chevallier et al., (2010, JGR) for more details.

Response: We can evaluate the quality of inverted carbon flux indirectly by comparing the posterior CO_2 mixing ratio against observations. The reduction of bias of simulated mixing ratio with posterior flux should be a prerequisite for an inversion. We agree with the referee that it is not enough to simply use mixing ratio biases to draw conclusion on the improvement of posterior flux. Therefore, we have performed the poor-man’s inversion as a benchmark to evaluate our satellite retrievals-based inversions.

Line 454: It seems that in OCO-2, also the pattern of the bias is conserved and thus little spatial information on the fluxes was derived.

Response: Yes, the biases of simulated XCO_2 from OCO-2 inversion remain relatively large. As analyzed and discussed in the revised manuscript, there are relatively large positive biases between OCO-2 and TCCON retrievals, and quite small mismatches between prior simulated and OCO-2 XCO_2, thus consequently leading to small adjustments to the prior flux. (see Lines 415-430, 436-466)

Line 458-459：I think you mean the other way around Change the sentence to “, using the GEOS-Chem 4D-Var data assimilation 472-473)system."(472-473)

Response: We have changed the sentence to "using the GEOS-Chem 4D-Var data assimilation system." (see Lines 472-473)

Line 464：This is confusing. The land net flux is a positive number if one includes fossil fuels and biomass burning, and now it becomes larger in the inversions? I think you described the opposite in the text: the land sink increased from the prior and thus a smaller net land flux when all components are included.

Response: It should be "excluding fossil fuels and biomass burning". We have replaced including with excluding. (see Line 478)

Line 467-468: This is not a good representation of the data: the growth rate is a measured quantity in the atmosphere, and should be compared to the simulated mixing ratios at a set of background sites of one wants to comment on its realism. For the global total fluxes, one can compare them to GCP which is also a flux estimate. But please do not refer to a GCP global growth rate and mention it to be actually fluxes, this is incorrect.

Response: We now benchmark two satellite data based inversion with the poor man's inversion and no longer use GCP estimate as a standard. We have removed GCP related statement in the revised manuscript.

Line 470: delete "basically"

Response: We have deleted it. (see Line 483)

Line 470: Based on what metric do you qualify this as significant? Is the change outside the uncertainty specified? If the significance was not evaluated, then do not use this qualification.

Response: Use "significantly", we just tended to emphasize the large adjustment of priori flux made at northern and southern temperate regions in GOSAT inversion.

This wording may cause confusion. So we change it to “largely”. (see Line 484)

Line 480: "carbon fluxes of OCO-2 and GOSAT": this does not exist, these instruments measure radiances. Please rephrase more accurately.

Response: We have revised to “carbon fluxes estimated from OCO-2 and GOSAT XCO_2 retrievals”. (see Line 491)

Line 480: Again, based on what metric?

Response: With added inversion experiments, we can compare the simulated CO_2 field with posterior flux from four inversions against surface observations. The reduction of biases and standard deviations at global and regional scale could be taken as metric to do the evaluation. In the revised paper, we have added more detailed analysis and discussion of those statistics. (see Lines 406-430, 436-463)

Line 480: Again, I would bet that the poor man's inversion also causes such an improvement and it does not rely on these instruments at all...

Response: The poor man’s inversion does cause similar improvement in reducing bias. However, there is litter improvement in the standard deviation of mismatch. As shown in the revised manuscript, GOSAT inversion shows evident improvement over benchmark. (see Line 406-430, 436-463)

Line 484: This statement seems not true for GOSAT, for which biases seem to be equally large or even larger after the inversion.

Response: This statement is not clearly and may denotes improvement in Southern Hemisphere. Actually, we had hoped to point out the increase of biases by GOSAT inversion. In southern hemisphere, for GOSAT, the biases are indeed equally large or even larger after the inversion. We have corrected that sentence “biases are elevated to a certain extent to” to “biases are slightly increased”. (Line 495)

Reference:

Chevallier, F., Feng, L., Bösch, H., Palmer, P. I., and Rayner, P. J.: On the impact of transport model errors for the estimation of CO_2 surface fluxes from GOSAT observations, Geophys. Res. Lett., 37, L21803, https://doi.org/10.1029/2010GL044652, 2010.

Singh, K., Jardak, M., Sandu, A., Bowman, K., Lee, M., and Jones, D.: Construction of non-diagonal background error covariance matrices for global chemical data assimilation, Geosci. Model Dev., 4, 299-316, https://doi.org/10.5194/gmd-4-299-2011, 2011.

Terrestrial ecosystem carbon flux estimated using GOSAT and OCO-2 XCO_2 retrievals

Hengmao Wang[1], Fei Jiang[1,2*], Jun Wang[1], Weimin Ju[1], Jing M. Chen[1,3]

1 Jiangsu Provincial Key Laboratory of Geographic Information Science and Technology, International Institute for Earth System Science, Nanjing University, Nanjing, 210023, China
2 Jiangsu Center for Collaborative Innovation in Geographical Information Resource Development and Application, Nanjing, 210023, China
3, Department of Geography, University of Toronto, Toronto, Ontario M5S3G3, Canada

Abstract

In this study, both the Greenhouse Gases Observing Satellite (GOSAT) and the Orbiting Carbon Observatory 2 (OCO-2) XCO_2 retrievals produced by NASA Atmospheric CO_2 Observations from Space (ACOS) project (Version b7.3), are assimilated within the GEOS-Chem 4D-Var assimilation framework to constrain the terrestrial ecosystem carbon flux during Oct 1, 2014 to Dec 31, 2015. For the comparison, one inversion using in-situ CO_2 observations, and another for benchmark, using global atmospheric CO_2 growth rate, are also conducted. The estimated global and regional carbon fluxes for 2015 are shown and discussed. CO_2 observations from surface flask sites and XCO_2 retrievals from TCCON sites are used to evaluate the simulated concentrations with the posterior carbon fluxes. The results show that globally, the terrestrial ecosystem carbon sink (excluding biomass burning emissions) estimated from GOSAT data is stronger than that inferred from OCO-2 data, and the annual atmospheric CO_2 growth rate estimated from GOSAT data is more consistent with the benchmark inversion. Regionally, in most regions, the land sinks inferred from GOSAT data are also stronger than those from OCO-2 data. Compared with the prior fluxes, the carbon fluxes in northern temperate regions change the most, followed by tropical and southern temperate regions, and the smallest changes occur in boreal regions. In temperate regions, the prior land sinks are significantly

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* Corresponding author: Tel.: +86-25-83597077; Fax: +86-25-83592288; E-mail address: jiangf@nju.edu.cn

increased, while in tropical regions the prior land sinks are decreased. The different changes in different regions are mainly related to the spatial coverage, the data amount, and the biases of these two satellites XCO_2 retrievals. Evaluations using flask and TCCON observations and the comparisons with in situ and benchmark inversions suggest that GOSAT data, can effectively improve the carbon flux estimates in the northern hemisphere.

Keywords: Terrestrial ecosystem carbon flux, inversion, GOSAT, OCO-2, GEOS-Chem

1. Introduction

Atmospheric inverse modeling is an effective method for quantifying surface carbon fluxes at global and regional scales using the gradient of CO_2 measurements. Inversion studies based on in-situ CO_2 observations agree well on global carbon budget estimates but differ greatly on regional carbon flux estimates and the partitioning of land and ocean fluxes as well, mainly due to the sparseness of observations in tropics, southern hemisphere oceans and the majority of continental interiors such as those in South America, Africa, and Boreal Asia (Peylin el al., 2013). Satellite observations offer an attractive means to constrain atmospheric inversions with their extensive spatial coverage over remote regions. Studies have shown that, theoretically, satellite observations, though with lower precision than in-situ measurements, can improve the carbon flux estimates (Rayner and O Brien, 2001; Pak and Prather, 2001; Houweling et al., 2004; Baker et al., 2006; Chevallier et al., 2007; Miller et al., 2007; Kadygrov et al., 2009; Hungershoefer et al., 2010).

Satellite sensors designed specifically to retrieve atmospheric CO_2 concentrations, have been in operation in recent years. The Greenhouse Gases Observing Satellite (GOSAT) (Kuze et al., 2009), being the first satellite mission dedicated to observing CO_2 from space, was launched in 2009. The National Aeronautics and Space Administration (NASA) launched the Orbiting Carbon Observatory 2 (OCO-2) satellite in 2014 (Crisp et al., 2017; Eldering et al., 2017). China's first CO_2 monitoring satellite (TanSat) was launched in 2016 (Wang et al., 2017; Yang et al., 2017). These satellites measure near-infrared sunlight reflected from the surface in CO_2 spectral bands and the O_2 A-band to retrieve column-averaged dry-air mole fractions of CO_2 (XCO_2), aiming to improving the estimation of spatial and temporal distributions of carbon sinks and sources. A number of inversions have utilized GOSAT XCO_2 retrievals to infer surface carbon fluxes (Basu et al., 2013; Maksyutov et al., 2013; Saeki et al., 2013; Chevallier et al., 2014; Deng et al., 2014; Houweling et al., 2015; Deng et al, 2016). Although large uncertainty reductions were achieved for regions which are under-sampled by in-situ observations, these studies didn't give robust regional carbon flux estimates. There are large spreads in regional flux estimates in some regions among these inversions. Furthermore, regional flux distributions inferred from GOSAT XCO_2 data are significantly different from those inferred from in-situ observations. For instance, several studies using GOSAT retrievals reported a larger than expected carbon sink in Europe (Basu et al., 2013; Chevallier et al., 2014; Deng et al., 2014; Houweling et al., 2015). The validity of this large Europe carbon sink derived from GOSAT retrievals is in intense debate and efforts to improve the accuracy of Europe carbon sink estimate are still ongoing (Reuter et al., 2014; Feng et al., 2016; Reuter et al., 2017).

Compared with GOSAT, OCO-2 has a higher sensitivity to column CO_2, much finer footprints and more extended spatial coverage, and thus has the potential to better constrain the surface carbon flux inversion (Eldering et al., 2017). Studies have used OCO-2 XCO_2 data to estimate carbon flux anomalies during recent El Nino events (Chatterjee et al., 2017; Patra et al., 2017; Heymann et al., 2017; Liu et al., 2017). Nassar et al. (2017) applied OCO-2 XCO_2 data to infer emissions from large power plants. Miller et al. (2018) evaluated the potential of OCO-2 XCO_2 data in constraining regional biospheric CO_2 fluxes and found that in the current state of development, OCO-2 observations can only provide a reliable constraint on CO_2 budget at continental and hemispheric scales. At present, it is still not clear whether with the improved monitoring capabilities, current OCO-2 observations have a greater potential than GOSAT observations for estimating CO_2 flux at regional or finer scale. It is therefore important to investigate how current OCO-2 XCO_2 data differ from GOSAT XCO_2 data in constraining carbon budget.

In this study, we evaluate the performance of GOSAT and OCO-2 XCO_2 data in constraining terrestrial ecosystem carbon flux. GOSAT and OCO-2 XCO_2 retrievals produced by the NASA Atmospheric CO_2 Observations from Space (ACOS) team are applied to infer monthly terrestrial ecosystem carbon sinks and sources from Oct, 2014 through December, 2015, using a 4D-Var scheme based on the GEOS-Chem Adjoint model (Henze et al., 2007). To evaluate the performance of satellite XCO_2 data based inversions, we conduct two additional inversions using in situ measurements and the global CO_2 trend, respectively. For simplicity, four inversions are referred as OCO-2 inversion, GOSAT inversion, in situ inversion and benchmark inversion, respectively. Inversion results are also evaluated against surface flask CO_2 observations and Total Carbon Column Observing Network (TCCON) XCO_2 retrievals. This paper is organized as follows. Section 2 briefly introduces GOSAT and OCO-2 XCO_2 retrievals and the inversion methodology and settings. Results and discussions are presented in Section 3, and Conclusions are given in Section 4.

2. Data and Method

2.1 GOSAT and OCO-2 XCO_2 retrievals

Developed jointly by the National Institute for Environmental Studies (NIES), the Japanese Space Agency (JAXA) and the Ministry of the Environment (MOE) of Japan, GOSAT was designed to retrieve total column abundances of CO_2 and CH_4. The satellite flies at a 666 km altitude in a sun-synchronous orbit with 98° inclination that crosses the equator at 12:49 local time. It covers the whole globe in three days and has a footprint of 10.5 km^2 at nadir. OCO-2 is NASA’s first mission dedicated to retrieving atmospheric CO_2 concentration. It flies at 705 km altitude in a sun-synchronous orbit with an overpass time at approximately 13:30 local time and a repeat cycle of 16 days. Its grating spectrometer measures reflected sunlight in three near-infrared regions (0.765, 1.61

and 2.06 μm) to retrieve XCO_2. OCO-2 has a footprint of 1.29×2.25 km^2 at nadir and acquires eight cross-track footprints creating a swath width of 10.3 km.

Both GOSAT and OCO-2 XCO_2 products were created using the same retrieval algorithm, which is based on a Bayesian optimal estimation approach (Roggers et al., 2000; O Dell et al., 2011). The GOSAT and OCO-2 XCO_2 data used in this study are Version 7.3 Level 2 Lite products at the pixel level. The XCO_2 data from lite products are bias-corrected (Wunch et al., 2011). Before being used in our inversion system, the data are processed in three steps. First, the retrievals for the glint soundings over oceans have relatively larger uncertainty, thus the data over oceans are not used in our inversions (Wunch et al., 2017). Second, in order to achieve the most extensive spatial coverage with the assurance of using best quality data available, the XCO_2 data are filtered with two parameters, namely warn_levels and xco2_quality_flag, which are provided along with the XCO_2 data. All data with xco2_quality_flag not equaling 0 are removed, the rest are divided into three groups according the value of warn_levels, namely group 1, group 2 and group 3. In group 1, the warn_levels are less than 8, in group 2, the warn_levels are greater than 9 and less than 12, and in group 3, those are greater than 13. Group 1 has the best data quality, followed by group 2, and group 3 is the worst. Third, the pixel data are averaged within the grid cell of 2°×2.5°, which is the resolution of the global atmospheric transport model used in this study. In each grid of 2°×2.5°, only the groups of best data quality are selected and then averaged. The other variables like column averaging kernel, retrieval error and so on which are provided along with the XCO_2 product are also dealt with the same method. Figures 1a and 1b show the coverages and data amount of GOSAT and OCO-2 XCO_2 data during the study period after processing. The filtered GOSAT and OCO-2 retrievals are not evenly distributed spatially. Due to the cloud contamination, there are few retrievals in a large portion of tropical land. In northern high latitude area, especially in boreal regions, due to the low soar zenith angle, available satellite retrievals are very sparse.

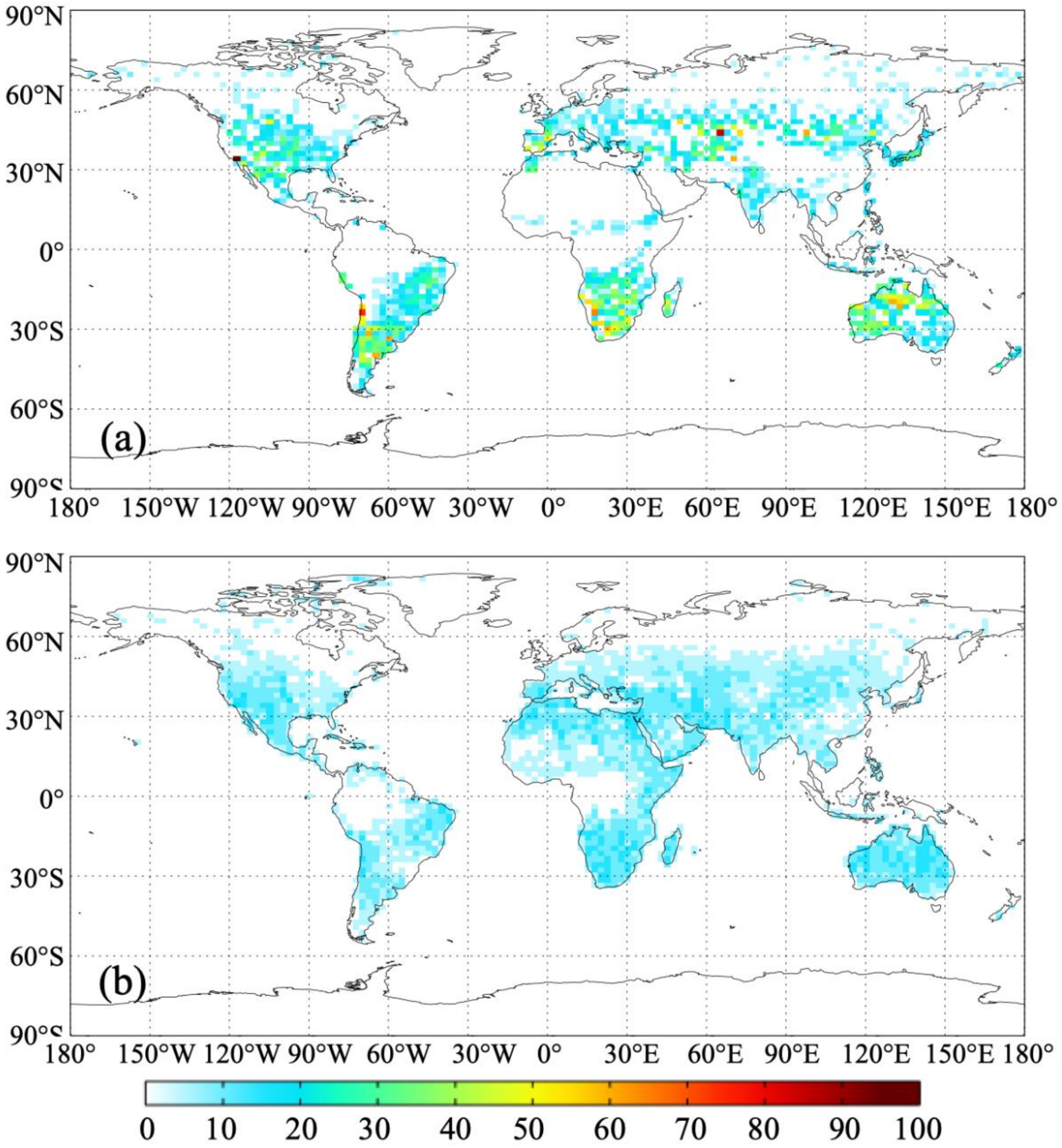

Figure 1. Data amount of each grid cell (2°×2.5°) of ACOS XCO_2 used in this study (a, GOSAT; b, OCO-2)

2.2 Surface observations and TCCON XCO_2 retrievals

Surface CO_2 observations are from the obspack_co2_1_CARBONTRACKER_CT2016_2017-02-06 product (ObsPackCT2016) (CarbonTracker Team, 2017), which was the observation data used in CarbonTracker 2016 (Peters et al., 2007, with updates documented at http://carbon-tracker.noaa.gov). It is a subset of the Observation Package (ObsPack) Data Product (ObsPack, 2016), and contains a collection of discrete and quasi-continuous measurements at surface, tower and ship sites contributed by national and universities laboratories around the world. In this study, in situ measurements from 78 sites provided by this product are used for inversion. Among these 78 sites, there are 56 flask sites, of which 52 sites are selected to evaluate the posterior CO_2 concentrations (selection criteria given in Section 4.3.1).

TCCON is a network of ground-based Fourier Transform Spectrometers that measure direct near-infrared solar absorption spectra. Column-averaged abundances of atmospheric constituents including CO_2, CH_4, N_2O, HF, CO, H_2O, and HDO are retrieved through these spectra. We use XCO_2 retrievals from 13 stations from TCCON GGG2014 dataset (Blumenstock et al., 2017; Deutscher et al., 2017; Griffith et al., 2017a, b; Kivi et al., 2017; Morino et al., 2017; Notholt et al., 2017a, b; Sherlock et al., 2017; Sussmann and Rettinger, 2017; Warneke et al., 2017; Wennberg et al., 2017a, b). The locations of in situ sites and 13 TCCON stations are shown in Figure 2.

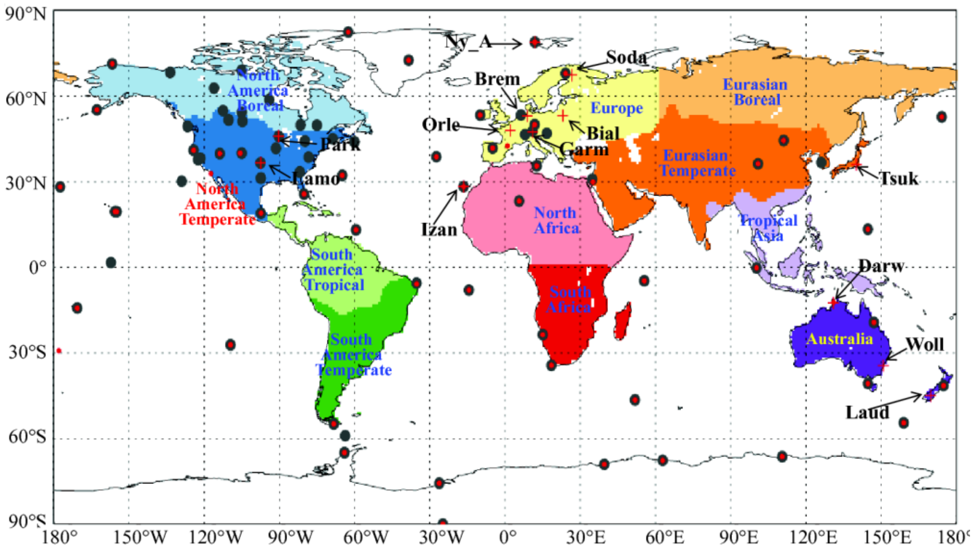

Figure 2. Distributions of the observation sites used in this study. Gray solid circles are surface sites used in the in situ inversion, red points and red cross marks are surface flask and TCCON sites used for evaluations, respectively, the shaded shows the 11 TRANSCOM regions

2.3 GEOS-Chem 4DVAR assimilation framework

2.3.1 GEOS-Chem model

GEOS-Chem model (http://geos-chem.org) is a global three-dimensional chemistry transport model (CTM), which is driven by assimilated meteorological data from the Goddard Earth Observing System (GEOS) of the NASA Global Modeling and Assimilation Office (GMAO) (Rienecker et al., 2008). The original CO_2 simulation in the GEOS-Chem model was developed by Suntharalingam et al. (2004) and accounts for CO_2 fluxes from fossil fuel combustion and cement production, biomass burning, terrestrial ecosystem exchange, ocean exchange and biofuel burning. Nassar et al. (2010) updated the CO_2 simulation with improved inventories. In addition to the inventories in earlier version, the new CO_2 fluxes includes CO_2 emissions from international shipping, aviation (3D) and the chemical production of CO_2 from CO oxidation throughout the troposphere. In most other models, the oxidation of CO was treated as direct surface CO_2 emissions. The details of the CO_2 simulation and the CO_2 sinks/sources inventories could be found in Nassar et al. (2010). The version of GEOS-Chem model used in this study is v8-02-01.

2.3.2 GEOS-Chem adjoint model

An adjoint model is used to calculate the gradient of a response function of one model scalar (or cost function) with respect to a set of model parameters. The adjoint of the GEOS-Chem model was first developed for inverse modeling of aerosol (or their precursors) and gas emissions (Henze et al., 2007). It has been implemented to constrain sources of species such as CO, CH_4, and O_3 with satellite observations (Kopacz et al., 2009, 2010; Jiang et al., 2011; Wecht et al., 2012; Parrington et al., 2012). Several studies have successfully used this adjoint model to constraint carbon sources and sinks with surface flask measurements of CO_2 mixing ratio and space-based XCO_2 retrievals (Deng et al., 2014; Liu et al., 2014; Deng et al., 2016; Liu et al., 2017).

2.3.3 Inversion method

In the GEOS-Chem inverse modeling framework, the 4D-Var data assimilation technique is employed for combining observations and simulations to seek a best optimal estimation of the state of a system. The scaling factors are applied to the carbon flux components to be optimized monthly in each model grid point. This approach seeks the scaling factors of the carbon flux that minimize the cost function, J, given by:

$$J(\mathrm{c}) = \frac{1}{2}\sum_{i=1}^{N}\left(XCO_{2,i}^{m} - XCO_{2,i}^{obs}\right)S_{obs,i}^{-1}\left(XCO_{2,i}^{m} - XCO_{2,i}^{obs}\right) + \left(\frac{1}{2}(c - c_a)S_c^{-1}(c - c_a)\right)$$

where N is total number of satellite XCO_2 observations; XCO_2^m and XCO_2^{obs} are modeled and observed total column averaged dry air mole faction of CO_2 respectively; c_a is the prior scaling factor of the carbon flux, which is typically set as unity; S_{obs} is the model-data mismatch error covariance matrix; S_c is the scaling factor error covariance matrix. The gradients of the cost function with respect to scaling factors calculated with the adjoint model are supplied to an optimization routine (the L-BFGS-B optimization routine; Byrd et al., 1995; Zhu et al., 1994), and the minimum of the cost function is sought iteratively.

For the modeled CO_2 column to be comparable with the satellite XCO_2 retrievals, the modeled CO_2 concentration profile should be first mapped into the satellite retrieval levels and then convoluted with retrieval averaging kernels. The modeled XCO_2 is computed by:

$$XCO_2^m = XCO_2^a + \sum_j h_j a_j\left(A(x) - y_{a,j}\right)$$

where *j* denotes retrieval level, *x* is the modeled CO_2 profile; *A(x)* is a mapping matrix; XCO_2^a is prior XCO_2, h_j is pressure weighting function, a_j is the satellite column averaging kernel and y_a is the prior CO_2 profile for retrieval. These last four quantities are provided from ACOS Version 7.3 Level 2 Lite products.

3. Inversion settings

In this study, the GEOS-Chem model was run in a horizontal resolution of 2°×2.5° for 47 vertical layers. Four inversions, using GOSAT data, OCO-2 data, in-situ measurements and global atmospheric CO_2 trend, are conducted from Oct 1, 2014 to December 31, 2015, respectively. The posterior dry air mole fraction of CO_2 on Oct 1, 2014 from CT2016 product is taken as the initial concentration. The first three months are taken as the spin-up period. The prior carbon fluxes used in this study include fossil fuel CO_2 emissions, biomass burning CO_2 emissions, terrestrial ecosystem carbon exchange and CO_2 flux exchange over the sea surface. Fossil fuel emissions are obtained from CT2016, which is an average of Carbon Dioxide Information Analysis Center (CDIAC) product (Andres et al., 2011) and Open-source Data Inventory of Anthropogenic CO_2 (ODIAC) emission product (Oda and Maksyutov, 2011). The biomass burning CO_2 emissions are also taken from CT2016, which are the average of the Global Fire Emissions Database version 4.1 (GFEDv4) (van der Werf et al., 2010; Giglio et al., 2013) and the Global Fire Emission Database from NASA Carbon Monitoring System (GFED_CMS). The 3-hourly terrestrial ecosystem carbon exchanges are from the Carnegie-Ames-Stanford Approach (CASA) model GFED4.1 simulation (Potter el al., 1993; van der Werf et al., 2010). CO_2 exchanges over the ocean surface are from the posterior air-sea CO_2 flux of CT2016. It is noted that the fossil fuel emissions and the biomass burning emissions in our inversions are kept intact. Both terrestrial ecosystem CO_2 exchanges and ocean flux are optimized in our inversions.

An efficient computational procedure for constructing non-diagonal scaling factor error covariance matrix which accounts for the spatial correlation of errors is implemented (Single et al., 2011). The construction is based on the assumption of exponential decay of error correlations. Other than forming covariance matrix explicitly, multiple-dimensional correlations are represented by tensor products of one-dimensional correlation matrices along longitude and latitudinal directions. For the two inversions, the scale lengths assigned along longitudinal and latitudinal directions are 500 km and 400 km for terrestrial ecosystem exchange and 1000 km and 800 km for ocean exchange, respectively. No correlations between different types of fluxes are assumed. The temporal correlations are also neglected. Global annual uncertainty of 100% and 40% are assigned for terrestrial ecosystem and ocean CO_2 exchanges, respectively (Deng and Chen, 2011). Accordingly, the uncertainty of scaling factor for the prior land and ocean fluxes in each month at the grid cell level are assigned to 3 and 5, respectively.

3.1 Inversions using satellite XCO_2 retrievals

The observation error covariance matrix is constructed using the retrieval errors, which are provided along with the ACOS XCO_2 data. Observation errors are assumed to be uncorrelated at model grid level. To account for the correlated observation errors, as shown in section 2.1, the pixel level retrieval errors are filtered and averaged to the model grid level, and then inflated by a factor of 1.9 to ensure the chi-square testing of χ^2 value to be close to 1 (Tarantola, 2004; Chevallier et al., 2007).

3.2 Inversion using in situ measurements

As descripted in section 2.2, surface CO_2 observations from 78 sites including flask samples and by quasi-continuous analyzer are adopted in this inversion. These data are selected from data collection of the ObsPackCT2016. The observation uncertainties of the 78 sites are also obtained from this product, which account for both the measurement and representative errors (Peters et al., 2007, with updates documented at http://carbontracker.noaa.gov). An examination for the differences between observations and forward model simulation was conducted (data not shown), and the results shows that observation uncertainties from CT2016 represents well with the model-data mismatch errors of GEOS-Chem model. In addition, we neglect correlations between observations and assume a diagonal observation error covariance matrix.

3.3 Benchmark inversion

A baseline inversion, which was introduced by Chevallier et al. (2009) as a Poor Man's method, is implemented to evaluate satellite retrievals and in situ measurements based inversions. Usually, the posteriori fluxes are evaluated by the improvement on the simulated CO_2 mixing ratios. Since the global CO_2 trend can be accurately estimated from marine sites, it is important to assess whether the inverted flux can capture more information than this trend. In this baseline inversion, the ocean flux is kept identical to the prior ones. The poor man's inverted land flux F_{pm} at location

(x, y) and at time t is defined as:

$$F_{pm}(x,y,t) = F_{piror}(x,y,t) + k \times \sigma(x,y,t)$$

where F_{prior} is the prior flux, σ is the uncertainty of the prior flux, k is a coefficient. Here k is determined by trial and error so that the mean annual global total of the poor man's fluxes equals the mean global total given by the annual global CO_2 growth rate from the Global Monitoring Division (GMD) of NOAA/Earth System Research Laboratory (ESRL) (Ed Dlugokencky and Pieter Tans, NOAA/ESRL, www.esrl.noaa.gov/gmd/ccgg/trends/). The annual global CO_2 growth rate is 2.96 ppm in 2015, which is converted to 6.28 PgC yr^{-1} for the poor man's global total by multiply by a factor of 2.123 PgC ppm^{-1}. In practice, this method distributes the land carbon sink according to the gross carbon fluxes from the vegetation.

4. Results and Discussions

4.1 Global carbon budget

Table 1 presents the inverted global carbon budgets in 2015 from four inversions. The global land sinks inferred by GOSAT and OCO-2 XCO_2 retrievals are -3.48 and -2.94 PgC yr^{-1}, respectively, which are both larger than the prior value, and lower than the estimate from the in-situ inversion. The global net flux from the benchmark inversion is inferred from the global annual CO_2 growth rate, which represents relatively accurately the net carbon flux added into atmosphere. It could be found that the global net flux from GOSAT inversion is the closest to the benchmark inversion estimate, while that from OCO-2 inversion is higher and the in situ inversion estimate is lower than the benchmark estimate. The differences of ocean fluxes among a priori and two inversions are small since we don't assimilate XCO_2 data over ocean. Therefore, the differences for the global net fluxes among the different experiments are similar to those of the global land sinks, indicating that GOSAT experiment has the best estimates for the land and ocean carbon uptakes, while those from in situ inversion are overestimated, and from OCO-2 inversion might be underestimated.

Table 1. Global carbon budgets estimated by the OCO-2 and GOSAT inversions in this study as well

as those from the prior fluxes, In situ and benchmark inversions (PgC yr^{-1})

	Prior	OCO-2	GOSAT	In situ	Benchmark
Fossil fuel and industry	9.84	9.84	9.84	9.84	9.84
Biomass burning emissions	2.20	2.20	2.20	2.20	2.20
Land sink	-2.50	-2.94	-3.48	-3.63	-3.35
Ocean sink	-2.41	-2.44	-2.45	-2.41	-2.41
Global net flux	7.13	6.66	6.11	6.00	6.28

4.2 **Regional carbon flux**

Figure 3 shows the distributions of annual land and ocean carbon fluxes (excluding fossil fuel and biomass burning carbon emissions, same thereafter) of the prior and the estimates using GOSAT and OCO-2 data. It could be found that compared with the prior fluxes, the carbon sinks in Central America, south and northeast China, east and central Europe, south Russia and east Brazil are obviously increased in GOSAT inversion. Except for east Brazil, the land sinks in those areas in OCO-2 inversion are also increased, but much weaker than those in GOSAT inversion, and in east Brazil, it turns to a significant carbon source. In contrast, in east and central Canada, north Russia, north Europe, west Indo-China Peninsula, north Democratic Republic of the Congo and west Brazil, their carbon sources are significantly increased in both GOSAT and OCO-2 inversions. In east and central Canada, north Europe and west Brazil, there are much stronger carbon sources in OCO-2 inversion.

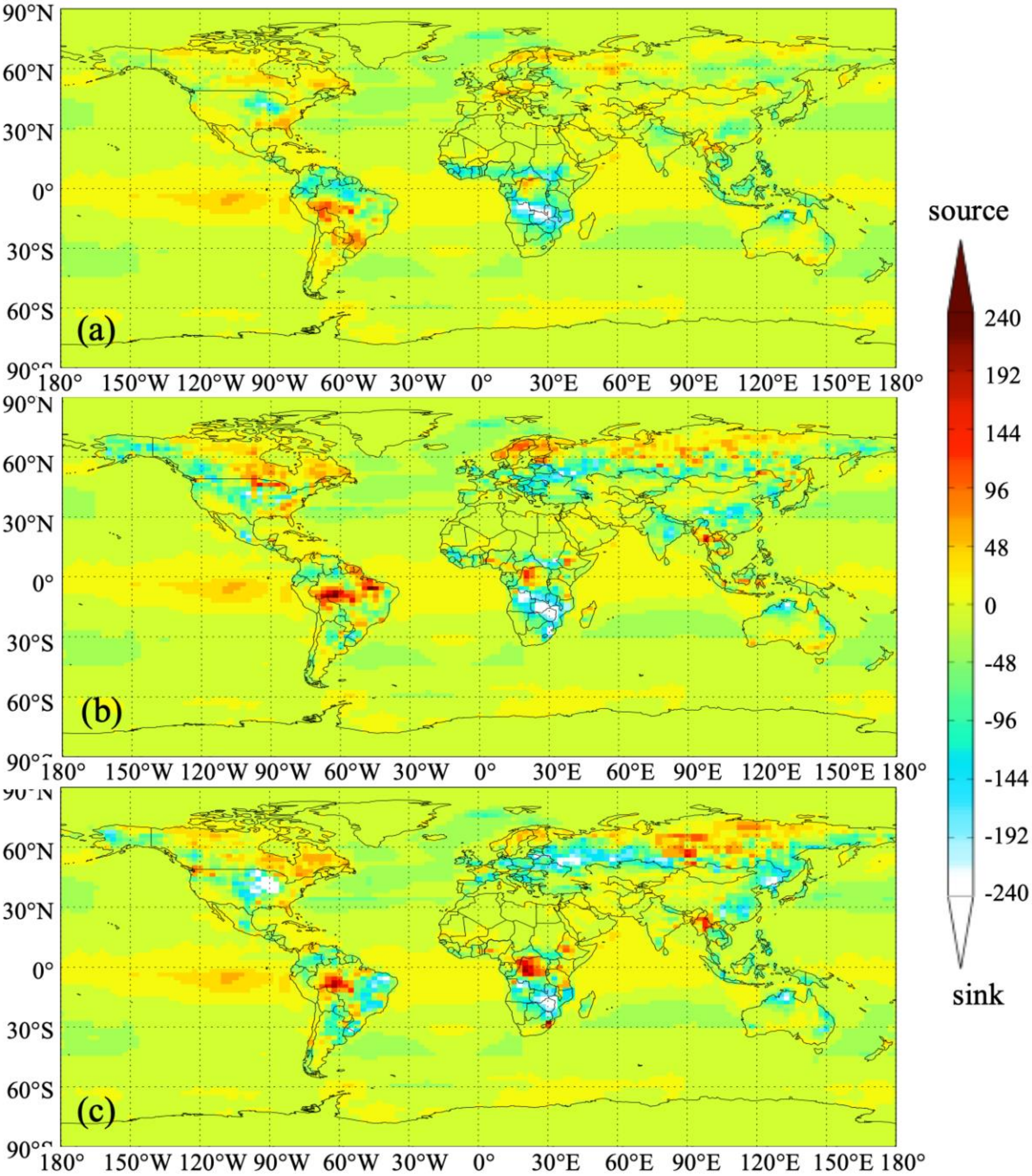

Figure 3. Distributions of annual land and ocean carbon fluxes a) prior flux and posterior fluxes based on (b) OCO-2 and (c) GOSAT data (gC $m^{-2}yr^{-1}$)

To better investigate the differences between GOSAT and OCO-2 inversions as well as their differences with the prior fluxes and two other inversions, we aggregate the prior and inferred land fluxes into 11 TRANSCOM land regions (Gurney et al., 2002) as shown in Figure 2. Figure 4 shows aggregated annual land surface fluxes from the prior and four inversions for the 11 land regions. Clearly, in most regions, the land sinks inverted based on GOSAT data are stronger than those inferred from OCO-2 data, especially in the Temperate and Tropical Lands. For example, in South America Temperate, the estimated land sink based on GOSAT data is about 4 times as large as the OCO-2 inversions; in North America Temperate and Tropical Asia, the carbon sinks of GOSAT experiment is about twice that of the OCO-2 inversions; and in South America Tropical, the OCO-2 inversion result is a carbon source of 0.19 PgC yr^{-1}, while GOSAT inversion gives a weak sink of -0.05 Pg C yr^{-1}. The total sinks of the Temperate/Tropical Lands optimized using GOSAT and OCO-2 XCO$_2$ retrievals are -2.95/-0.36 and -2.59/-0.20 Pg C yr^{-1}, respectively (Table 2). In Northern Boreal Land, the total carbon sinks inverted with GOSAT and OCO-2 data are comparable. However, the two XCO$_2$ data have opposite performances in two northern boreal regions, namely in Eurasian Boreal, the inverted land sink with GOSAT is stronger than that with OCO-2; while in North America Boreal, it is the opposite.

For different continents (Table 2), in Asia and Australia, their carbon sinks inverted from GOSAT and OCO-2 data are comparable. In North America, South America and Europe, the land sinks in GOSAT inversion are much stronger than those in OCO-2 inversion. Especially in South America, the GOSAT inversion result is a strong carbon sink (-0.51 Pg C yr^{-1}), while in OCO-2 inversion, it is a weak carbon source (0.06 Pg C yr^{-1}). Conversely, in Africa, the land sink estimated with GOSAT data is much weaker than those from OCO-2 data, the former (-0.59 Pg C yr^{-1}) being only about the half of the latter (-1.13 Pg C yr^{-1}).

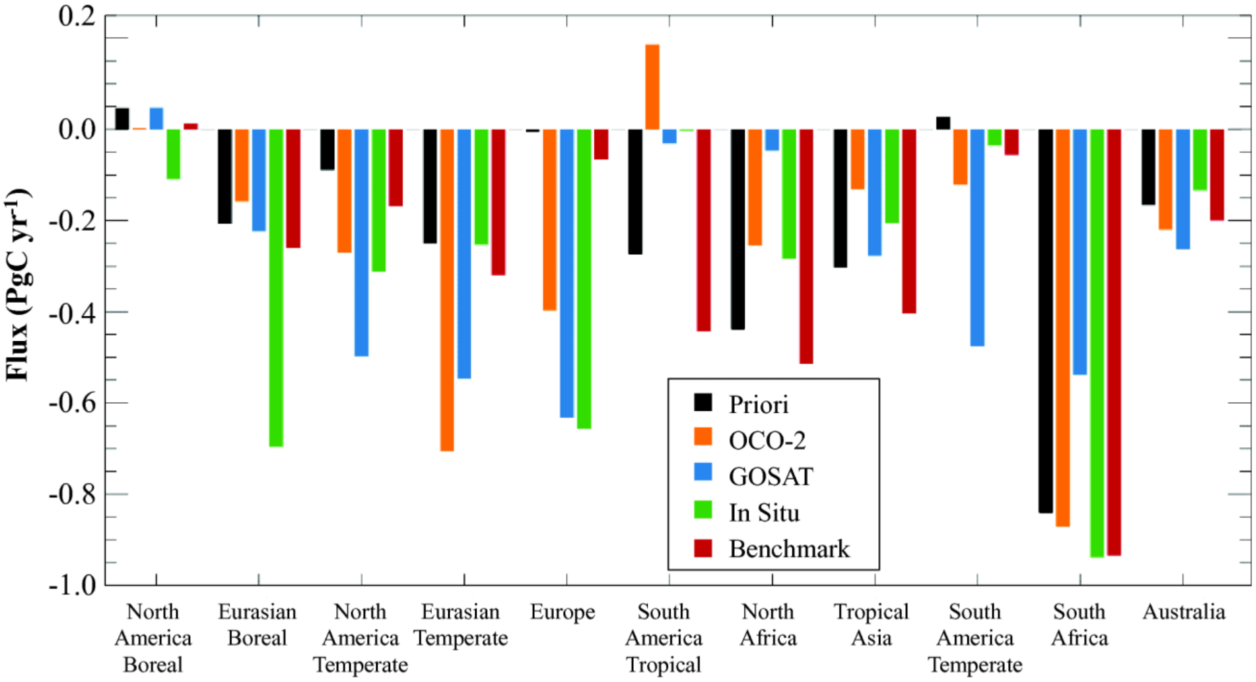

Figure 4. Aggregated annual land fluxes of the 11 TRANSCOM land regions

Table 2. The prior and posterior fluxes in six continents and boreal, temperate and tropical lands

Regions	Prior	OCO-2	GOSAT	In situ	Benchmark
North America	-0.04	-0.27	-0.45	-0.42	-0.15
South America	-0.25	0.06	-0.51	-0.04	-0.50
Europe	-0.01	-0.40	-0.63	-0.66	-0.07
Asia	-0.76	-0.99	-1.05	-1.16	-0.98
Africa	-1.28	-1.13	-0.58	-1.22	-1.45
Australia	-0.17	-0.22	-0.26	-0.13	-0.20
Northern Boreal Land	-0.16	-0.16	-0.18	-0.81	-0.25
Northern Temperate Land	-0.35	-1.37	-1.68	-1.22	-0.55
Tropical Land	-1.01	-0.20	-0.36	-0.49	-1.36
Southern Temperate Land	-0.98	-1.21	-1.28	-1.11	-1.20

Compared with the in situ and benchmark inversions, in the boreal regions, the land sinks estimated using in situ observations are much stronger than those of OCO-2 and GOSAT inversions, but close to the benchmark results. In the temperate lands, except for South Africa, the GOSAT results are much stronger than those of the in situ and benchmark experiments, especially in South America Temperate, GOSAT inversion shows a strong carbon sink, while in situ experiment shows a weak source and benchmark experiment shows a weak sink. On the contrary, in the tropical regions, the land sinks inferred from both OCO-2 and GOSAT experiments are weaker than the in situ and benchmark inversions.

Compared with the prior fluxes, the inferred land fluxes in Northern Temperate regions have the largest changes, followed by those in Tropical regions and Southern Temperate lands, while in boreal regions, the changes are the smallest. As shown in Table 3, for different TRANSCOM regions and different XCO_2 used, the changes of carbon fluxes have large differences. Since the same setup used in these two inversions and the same algorithm adopted for retrieving XCO_2 from GOSAT and OCO-2 measurements, the different impacts of XCO_2 data on land sinks may be related to the spatial coverage and the amount of data in these two XCO_2 datasets. As shown in Figure 1, in different latitude zones, the spatial coverage and the data amount of GOSAT and OCO-2 have large differences. Statistics show that the amount of data is largest in northern temperate land, followed by southern temperate land and tropical land, and least in northern boreal regions, corresponding to the magnitude of changes of carbon fluxes in these zones. For one specific zone, the different impacts of these two XCO_2 datasets may be also related to their data amount. For example, in northern temperate land, GOSAT has more XCO_2 data than OCO-2. Accordingly, the change of carbon flux caused by GOSAT is larger than that caused by OCO-2. Conversely, in Tropical Land, OCO-2 has more data than GOSAT, and as shown before it has more significant impact on the land sink. This relationship could also be found in each TRANSCOM region. Figure 5 gives a relationship between the XCO_2 data amount ratios of GOSAT to OCO-2 and the land sinks absolute change ratios caused by GOSAT to OCO-2 for 11 TRANSCOM land regions. Obviously, except for North and South Africa, there is a significant linear correlation (R=0.95) between these two ratios, suggesting that with more XCO_2 data, the more carbon flux relative to the prior flux is changed. In North Africa, we find that OCO-2 has better spatial coverage and more data than GOSAT, as shown in Figure 1. Although the differences mainly occur in the Sahara where the carbon flux is very weak, but near the equatorial region where the carbon flux is large, OCO-2 still has more data than GOSAT. In southern Africa, both XCO_2 have good spatial coverage, the amount of GOSAT data is about 1.5 times that of OCO-2, but the changes in the carbon flux caused by GOSAT is about 10 times that of OCO-2. The large ratio of carbon change is mainly due to the relatively small carbon change from OCO-2 inversion.

Table 3. Differences between the inferred and the prior carbon fluxes, the data amount of XCO_2 and the deviations between the modeled with prior flux and satellite retrieved XCO_2 in different regions

Region	**Flux changed (Pg C yr^{-1})***		**XCO_2 data amount**		**Deviations (ppm)****	
	OCO-2	**GOSAT**	**OCO-2**	**GOSAT**	**OCO-2**	**GOSAT**
North America Boreal	-0.05	0	1143	639	0.6	1.41
North America Temperate	-0.18	-0.41	2390	3163	0.52	0.93
South America Tropical	0.46	0.24	800	421	-0.89	0.43
South America Temperate	-0.15	-0.5	1711	3500	0.02	0.54
North Africa	0.19	0.39	3208	674	0.12	-0.19
South Africa	-0.03	0.3	2057	3060	0.17	0.33
Eurasian Boreal	0.05	-0.02	1714	1339	0.47	1.5
Eurasian Temperate	-0.46	-0.3	5323	4782	0.46	0.82
Tropical Asia	0.17	0.03	726	550	-0.43	0.34
Australia	-0.05	-0.1	2011	3110	0.18	0.67
Europe	-0.39	-0.63	1604	2106	0.28	1.35
Global land	-0.44	-0.98	22687	23344	0.22	0.79
Northern Boreal Land	0.005	-0.02	2857	1978	0.52	1.47
Northern Temperate Land	-1.03	-1.33	9317	10051	0.45	0.96
Tropical Land	0.82	0.66	4734	1645	-0.08	0.13
Southern Temperate Land	-0.23	-0.3	5779	9670	0.11	0.6

* Differences between posterior and prior flux

** Deviations between the modeled with prior flux and satellite retrieved XCO_2

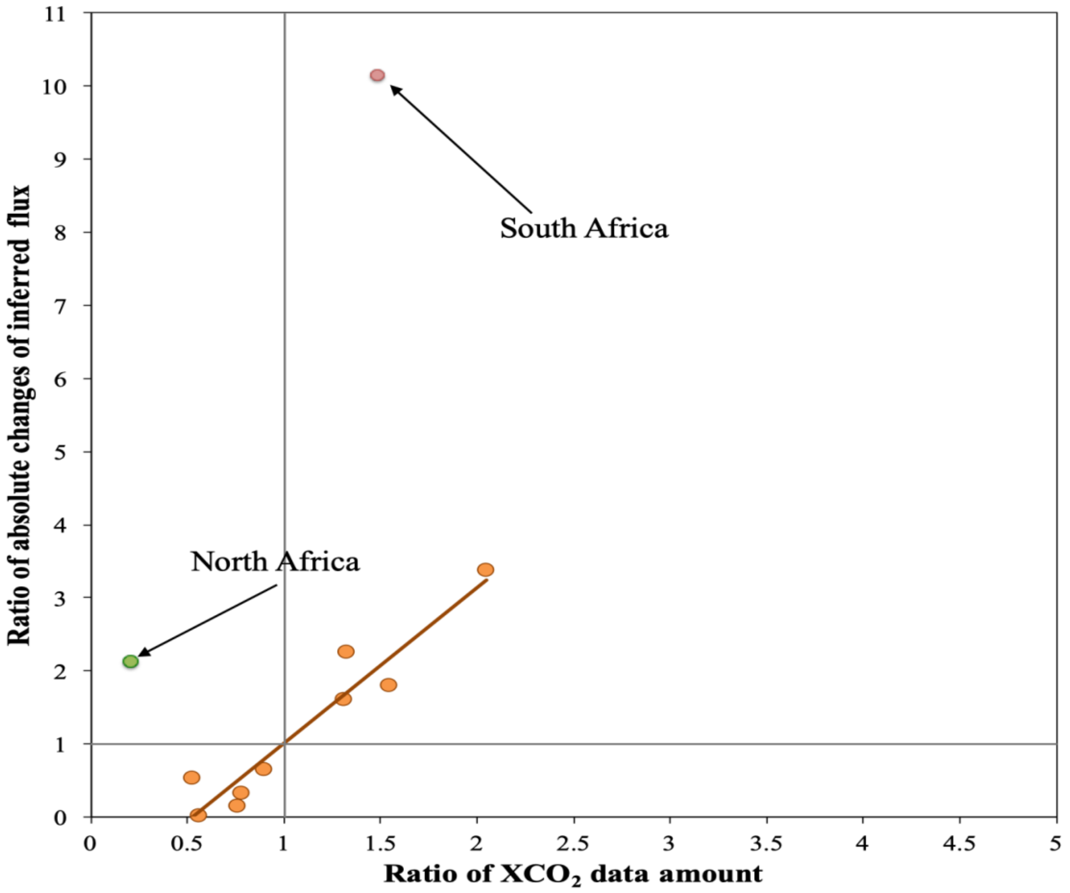

Figure 5. Scatter plot for the ratio of GOSAT to OCO-2 XCO_2 data amount versus the ratio of absolute changes of the land sinks caused by GOSAT to OCO-2 in the 11 TRANSCOM land regions

In addition to the data amount, the deviations between the simulated CO_2 concentrations using prior fluxes and the satellite retrievals should be another reason to explain the performances of OCO-2 and GOSAT retrievals in different regions. Usually, a large model-data mismatch will impose strong constraint on the prior flux in inversions. Therefore, we compare the mismatches in OCO-2 and GOSAT inversions. The results are grouped global land and into the 11 TRANSCOM land regions, as shown in Table 3. The global land mean difference between modeled XCO_2 and the OCO-2 and GOSAT retrievals are 0.22 and 0.79 ppm, respectively, indicating that the GOSAT retrieval would have stronger constraint on the prior fluxes. In most TRANSCOM regions except North Africa, the mismatches in GOSAT inversion are positive and larger than those of OCO-2 inversion. In Tropic Asia and South America Tropic, the sizable negative mismatches in OCO-2 inversion could account for a weak inverted carbon sink and an inverted carbon source in these two regions, while in North Africa, the negative mismatch in GOSAT inversion may explain why a rather weak sink is inverted for this region. The difference of mismatch between OCO-2 and GOSAT inversions exhibits rather large spread, ranging from 0.16 to 1.33 pm, indicating the biases of two satellite XCO_2 retrievals differ greatly.

Table 4. Statistics of the OCO-2 and GOSAT retrievals uncertainties against the TCCON retrievals

	OCO-2			GOSAT		
	Bias/ppm	Stdev/ppm	N. of Obs.	Bias/ppm	Stdev/ppm	N. of Obs.
Bial	0.91	1.47	21	0.06	1.35	29
Darw	0.75	0.85	43	-0.41	1.62	44
Garm	-0.10	2.97	14	0.73	2.02	35
Lamo	0.04	1.09	56	-0.91	1.39	82
Laud	0.59	1.38	18	-0.79	1.70	30
Orle	1.49	1.18	24	-0.51	1.38	39
Park	0.50	1.26	29	-0.58	1.52	38
Soda	1.91	1.89	7	-0.54	2.58	9
Tsuk	0.93	1.95	16	-0.47	1.11	38
Woll	0.34	1.07	27	-0.36	1.56	45
All	0.60	1.45	255	-0.42	1.59	389

Moreover, the uncertainties of OCO-2 and GOSAT retrievals may be another reason for the different performances in these two inversion experiments. We use TCCON retrievals to evaluate the uncertainties of OCO-2 and GOSAT XCO_2 retrievals. For satellite retrievals falling in the model grid box where TCCON sites are located, the closest TCCON retrievals in time or within two hours of satellite overpass time are chosen for comparison. We follow the procedures in Appendix A of Wunch et al. (2011) to do both prior profile and averaging kernel corrections. Table 4 shows the biases and standard deviations grouped globally and at 10 TCCON sites where both OCO-2 and GOSAT retrievals are available for comparison. The locations of these 10 sites are shown in Figure 2. Overall, GOSAT retrievals (-0.46 ppm) have lower bias than OCO-2 retrievals (0.6 ppm). At most sites except Garm, OCO-2 retrievals have positive biases, while GOSAT retrievals tend to have negative bias except at Bial and Garm sites. It also could be found that the spread of GOSAT data biases are small, falling in the range of -0.36 to -0.58 ppm at most sites, while the spread of OCO_2 data biases is relatively large, with biases greater than 0.7 ppm at more than half of sites, in the range of 0.34 to0.59 pm at 3 sites.

4.3 Evaluation for the inversion results

4.3.1 Flask observations

As shown in section 2.2, Flask observations from 52 sites are used to evaluate the inversion results. Actually, there are much more flask observations in the dataset. When there are more than one flask dataset for one site, we give priority to that from NOAA/ESL or that with more consistent records. There are 56 sites with available flask observations for evaluation. In addition, during the evaluations, we find that GEOS-Chem model is unable to capture the variations of CO_2 mixing ratios at HPB, HUN, SGP and TAP sites, where the standard deviations of the deviations between the observed and modeled mixing ratio are larger than 5 ppm. Therefore, we exclude these four sites and use the rest 52 flask sites (shown in Figure 2) to evaluate the posterior mixing ratios. The GEOS-Chem model is driven with the prior flux and the four posterior fluxes to obtain the prior and posterior CO_2 mixing ratios. The simulated CO_2 mixing ratios are sampled at each observation site and within half an hour of observation time.

Table 5 shows a summary of comparisons of the simulated CO_2 mixing ratios against the flask measurements. The mean difference between the prior CO_2 mixing ratio and the flask measurements is 0.93ppm, with a standard deviation of 2.3 ppm. All four inversions show improvement in posterior concentrations with reductions of biases. Not surprisingly, in situ inversion, using surface observations, shows the best improvement in posterior CO_2 mixing ratio with the largest reduction of bias and standard deviation. GOSAT inversion achieve almost the same reductions of standard deviation as in situ inversion. OCO-2 inversion gives larger bias and standard deviation than in situ and GOSAT inversions. Benchmark inversion effectively reduces the bias but with little improvement in the reduction of standard deviations.

Figure 7 shows the biases at each observation site in different latitudes. It could be found that the biases between the simulations and the observations in the northern hemisphere are significantly larger than those in southern hemisphere since the carbon flux distribution of the northern hemisphere is more complex than that of the southern hemisphere. When the prior flux is used, almost all sites in the northern hemisphere have significant positive deviations, with an average of 1.7 ppm, while in the southern hemisphere, the deviations are very small, with an average bias of only 0.08 ppm; when using the posteriori flux from OCO-2 inversion, the deviations in most northern hemisphere sites are slightly reduced, with an average deviation of 0.85 ppm, while in the southern hemisphere, at most sites, the biases increase by variable amounts, with a mean of -0.13 ppm; when using the posterior flux from GOSAT inversion, the deviations are significantly reduced to -0.04 ppm in the northern hemisphere but further increased to -0.55 ppm in the southern hemisphere. In situ inversion shows similar improvement in Northern Hemisphere as GOSAT inversion does, but also with litter improvement in Southern Hemisphere. Though benchmark inversion effectively reduces the global bias, it shows limited improvement in the reduction of biases at most sites. These suggest that GOSAT and in situ inversions can effectively improve the carbon fluxes estimate in the northern hemisphere, but overestimate the land sinks in the southern hemisphere, especially for GOSAT inversion.

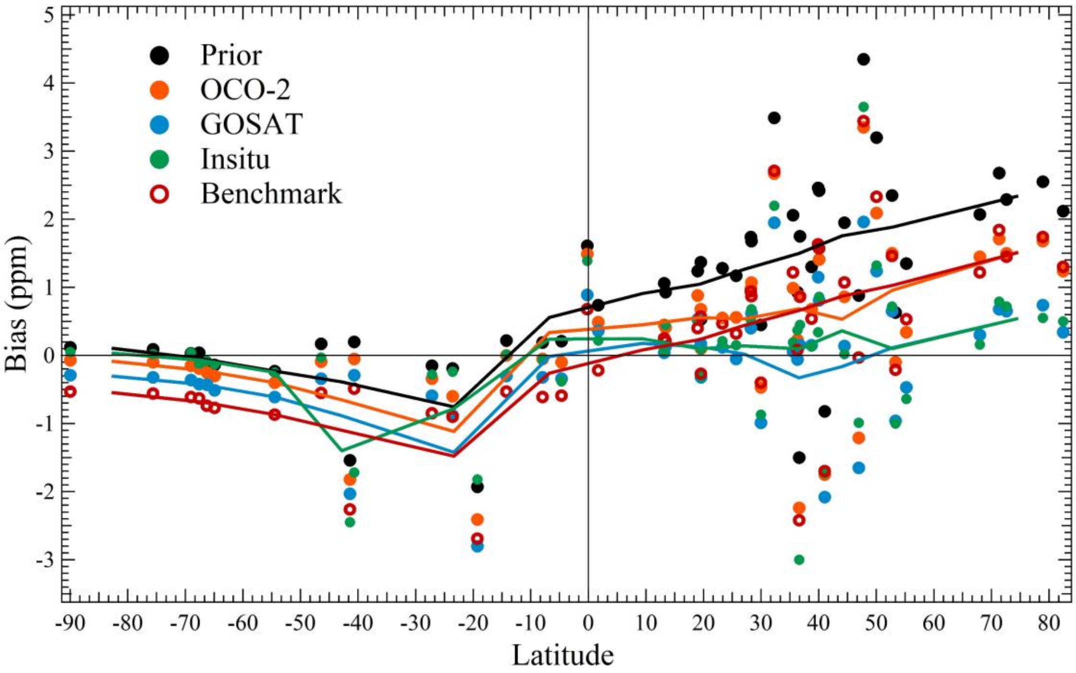

Figure 6. Biases of the simulated CO_2 mixing ratios against the flask measurements in different latitudes (positive/negative biases represent modeled concentration being greater/less than the observed, the different color lines are the smooth of the corresponding marks)

4.3.2 TCCON observations

We also use ground XCO_2 observations from 13 TCCON sites (Figure 2) to evaluate our inversion results. The simulated CO_2 concentrations at 47 vertical levels are mapped into 71 TCCON levels. Following the approach of Wunch et al. (2011), using prior profiles and the averaging kernel from the TCCON dataset, we calculated the modeled XCO_2 values at 13 TCCON sites. Table 5 shows the comparison of modeled XCO_2 with TCCON observations. The mean difference between prior XCO_2 and TCCON retrievals is 1.16 ppm, with a standard deviation of 1.3 ppm. GOSAT inversion performs the best with the largest reductions of bias and standard deviations. Though OCO-2 inversion shows improvement in the reduction of standard deviation, it gives a relative large bias for posterior XCO_2. In situ inversion has the same reduction of standard deviation as GOSAT inversion. Benchmark inversion reduces the bias to 0.49 ppm and gives slight improvement in reducing standard deviation of posterior XCO_2.

Figure 7 shows the bias at each TCCON site. Obviously, the biases at all TCCON sites are positive when using the prior fluxes, ranging between 0.3 and 2.6 ppm. The biases at the sites in the northern temperate and boreal areas are all above 1.5 ppm except for the Lamont site. In Northern Hemisphere, GOSAT, in situ and benchmark inversions significantly reduce the biases at most sites except Izan, Lamo and Park. However, the biases at those sites remain relatively large. Since GOSAT and in situ inversions show evident improvement at flask sites in Northern Hemisphere, the remaining large biases at TCCON sites may not be due to the underestimate of Northern Land sink but the uncertainty of TCCON retrievals. At Lamo and Park sites in North America, GOSAT inversion gives negative bias, suggesting it may overestimate the carbon sink for North America Temperate. At Izan, the biases of posterior concentrations are up to -0.5 ppm from in situ and benchmark inversions, indicating the overestimate of the carbon sink in North Africa by two inversions. For two of the three TCCON sites in the southern hemisphere, the biases are changed to negative values when using the posteriori fluxes from GOSAT data, further indicating the overestimation of carbon sinks by GOSAT data in the southern hemisphere.

Table 5. Statistics of the model-data mismatch errors at the 52 surface flask sites and the 13 TCCON sites

	Flask		TCCON	
	Bias	Stdev	Bias	Stdev
Prior	0.93	2.30	1.16	1.30
OCO-2	0.33	2.15	0.80	1.08
GOSAT	-0.19	2.05	0.22	1.04
In situ	-0.03	2.04	0.38	1.04
Benchmark	0.14	2.28	0.49	1.25

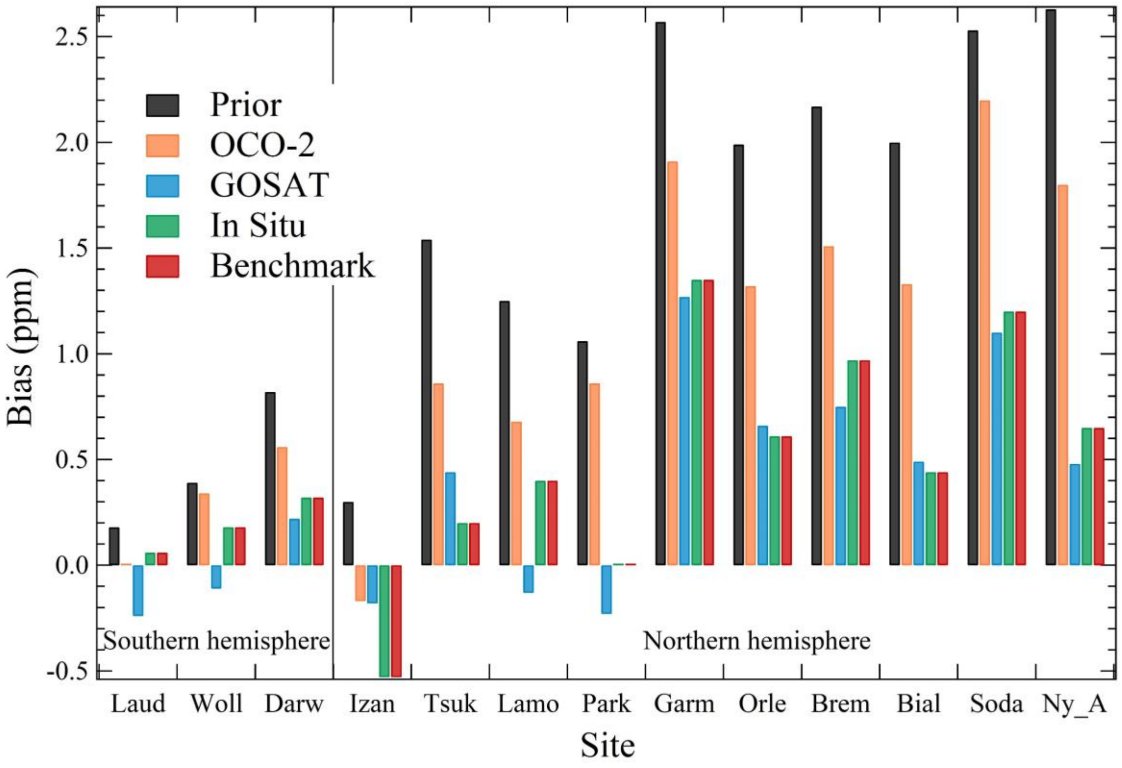

Figure 7. The biases between the modeled and observed XCO_2 at the 13 TCCON sites

5. Summary and Conclusions

In this study, we use both GOSAT and OCO-2 XCO_2 retrievals to constrain terrestrial ecosystem carbon fluxes from Oct 1, 2014 to Dec 31, 2015, using the GEOS-Chem 4D-Var data assimilation system. In addition, one inversion using in situ measurements and another inversion as a benchmark, are also conducted. The posterior carbon fluxes estimated from these four inversions at both global and regional scales during Jan 1 to Dec 31, 2015 are shown and discussed. We evaluate the posterior carbon fluxes by comparing the posterior CO_2 mixing ratios against observations from 52 surface flask sites and 13 TCCON sites.

Globally, the terrestrial ecosystem carbon sink (excluding biomass burning emissions) estimated from GOSAT data is stronger than that inferred from OCO-2 data and weaker than that from in situ inversion, but closest to the benchmark inversion estimate. Regionally, in most regions, the land sinks inferred from GOSAT data are also stronger than those from OCO-2 data. Compared with the in situ inversion, GOSAT inversions have weaker sinks in Boreal and most Tropical lands, and much stronger ones in Temperate lands. Compared with the prior fluxes, the inferred land sinks are largely increased in the temperate regions, and decreased in tropical regions. There are largest changes of the prior fluxes in Northern Temperate regions, followed by Tropical and Southern Temperate regions, and the weakest in boreal regions. The different impact of XCO_2 on the carbon fluxes in different regions is mainly related to the spatial coverage and the amount of XCO_2 data. Generally, a larger amount of XCO_2 data in a region is corresponding to a larger change in the inverted carbon flux in the same region. The different biases of the two XCO_2 retrievals may also give rise to their different inversion performances.

Evaluations of the inversions using CO_2 concentrations from flask measurements and TCCON retrievals show that both posterior carbon fluxes estimated from OCO-2 and GOSAT retrievals could improve the modeling of atmospheric CO_2 concentrations, and overall, the simulated CO_2 concentrations with GOSAT posterior fluxes are much closer to the observations than those with OCO-2 estimates. Compared with bench inversion, both GOSAT and in situ inversions show evident improvement with the similar reductions of both biases and standard deviations of posterior concentrations, while OCO-2 inversion displays limited improvement over benchmark inversion. Generally, the posterior biases from GOAST inversion are significantly reduced in the northern hemisphere and are slightly increased in the southern hemisphere. These suggest that GOSAT data can effectively improve the carbon fluxes estimate in the northern hemisphere.

The OCO-2 and GOSAT XCO_2 retrievals used in this study are bias-corrected products. Nevertheless, there still exists apparent biases and the differences between these two satellites data are distinctive. The more reliable constraints on carbon flux call for the further reduction of satellite retrieval errors. These indicate that we should interpret carbon flux inferred from the current satellites XCO_2 retrievals with great cautions in understanding global carbon cycle.

Author contributions

FJ and HW designed the research, HW conducted inverse modeling, HW and FJ conducted data analysis and wrote the paper, JW, WJ and JC participated in the discussion of the results and provided input on the paper for revision before submission.

Competing interests

The authors declare that they have no conflict of interest.

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