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 reorganized the section 4, we present the evaluation results first and then followed by the flux analysis and discussions.

2) For better clarity, we rewritten the abstract, we removed the statement on the differences between posterior fluxes from satellites and prior fluxes and focus more on the comparisons between satellites and in situ inversion.

3) We removed the comparisons between satellites inversions and poor-man inversion on regional carbon flux, but added more analysis about the comparisons between the satellites and in situ inversions.

4) We changed the statemen of "benchmark inversion" to "poor-man inversion", and made clear the purpose and the calculations of doing poor-man inversion.

5) We made the conclusion clear that GOSAT data can effectively improve the carbon flux estimates in Northern Hemisphere and its performance is close to in situ data, while OCO-2 data, with the specific version used in this study, shows only slight improvement.

6) We also checked errors and typos carefully and made the necessary corrections.

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 thank the anonymous referee for his/her valuable comments and constructive suggestions. 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 aim of the study is to provide a comparison of simulated CO2 concentrations estimated with inverse model using OCO-2 and GOSAT retrievals for the year 2015. The questions of interest to broader audience are differences in the amplitudes of respective flux corrections and their spatial distributions, as well as how well the optimized simulations agree with the observed concentrations by surface flask and TCCON networks. Authors discuss the spatial variability of the satellite data biases with respect to TCCON data and the biases in inverse model estimated concentrations with respect to surface flask and TCCON data. Based on comparison of the estimated fluxes to benchmark inversion and posterior fits to ground-based observational data not used in inversion, authors conclude that use of GOSAT data in inversion results in better fit to observations than OCO-2 data. The manuscript is been resubmitted and was substantially revised with respect to earlier version. Presentation of the material is clear and has improved over initial submission, so manuscript can be accepted after minor revisions. The text should also be checked for orthographical errors.

Response: We appreciate the referee's insightful comments. We checked for orthographical errors carefully and made the necessary corrections.

Detailed comments

L74 Authors consider if "current OCO-2 observations have a greater potential than GOSAT …". It would be useful to note what would be the reasons affecting usefulness of OCO-2 or GOSAT? Did they mean spatially and temporally varying biases?

Response: Yes, spatially and temporally varying biases affect usefulness of satellite retrievals greatly. As pointed out by Chevalier et al. (2007), biases of a few tenth of one ppm in XCO_2 could bias subcontinental flux estimates by several tenths of gigaton of carbon. Spatial coverage also affects the usefulness of satellite data, especially in regions with frequent clouds, where OCO-2 is anticipated to perform better. In the revised manuscript, we have changed that sentence to "it is still not clear whether with the improved monitoring capabilities and better spatial coverage, current OCO-2 observations have a greater potential than GOSAT observations for estimating CO_2 flux at regional or finer scale, since except spatial coverage, the biases also affect the usefulness of satellite retrievals greatly.". See lines 77-80, pages 3-4.

L454 Although results of the analysis support the conclusions, it should be noted that the study period of 2015 is characterized by strong El-Nino and the spatial distribution of fluxes typical for more common non El-Nino years, appears disturbed in the El-Nino year.

Response: Thanks for the referee for calling our attentions to the influence of El-Nino event. We understand the importance of evaluating performance of two satellite data in both El-Nino and non El-Nino years. However, the availability of overlap of OCO-2 and GOSAT data from ACOS for only 20 month prevents us from doing multi-year inversions.

L456 The uncertainty/bias in TCCON retrievals is cited, but evidence for the bias is not shown/discussed. Suggest to add some reference(s) on TCCON biases.

Response: TCCON retrievals are subject to air-mass dependent and air-mass independent biases. The correction factors are applied to the column-averaged mole fractions. The air-mass dependent correction factor is determined from the symmetric component of the diurnal variation. The air-mass-independent correction factor is determined by comparisons with in situ profiles measured over TCCON sites from aircraft or balloon payloads. The TCCON biases are usually evaluated by aircraft or balloon profile observations. However, the comprehensive evaluation of TCCON biases are still hindered from the lack of enough profile data. We have added two references of Wunch et al. (2010) and Messerschmidt et al. (2011) in the revised manuscript in line 336, page 15.

L490 Analysis of the posterior fit to surface flask observations in Southern and North hemispheres indicates there are biases in GOSAT and OCO-2, and those are changing in different directions. Comparison to TCCON show the retrieval bias difference between GOSAT and OCO-2 are in order of 1 ppm. It is worth noting that, while observed mean difference with TCCON calls for correction of the GOSAT and OCO-2 data, based on mean deviation from TCCON, it was not done in this study, as opposed to some other inverse modeling studies.

Response: The bias difference up to 1 ppm between GOSAT and OCO-2 retrievals against TCCON retrievals does seem rather large. However, due to limited number of collocated satellite retrievals, the sample size for computing bias is relatively small. Therefore, the large bias difference should be treated as a relative value. As shown in Table 4, when comparing to the same prior CO_2 mixing ratios, the difference of overall mismatches between GOSAT and OCO-2 data is 0.57 ppm, suggesting the bias difference might not be as large as shown by comparison with TCCON data. As described in Section 2, GOSAT and OCO-2 retrievals used in our inversions are already bias-corrected. The remaining biases of satellite retrievals suggest that the bias-correction scheme implemented need to be improved. However, due to the short time period of our inversions, the sparseness of TCCON sites and the lack of profile data, it is really difficult to figure out an appropriate way to further reduce satellite retrievals bias. The following sentences have been added in the revised manuscript to point out the deficiency of statistics, see lines 487-493, page 25.

"…It should be noted that due to the limited number of collocated satellite retrievals, the real bias difference might not be up to 1 ppm. As shown in Table 4, the difference of overall mismatches between GOSAT and OCO-2 data is 0.57 ppm. These indicate that although both OCO-2 and GO-SAT products were bias-corrected using TCCON retrievals, the uncertainties of OCO-2 and GO-SAT retrievals are still very large, especially for OCO-2 retrieval, resulting the worse performance of OCO-2 retrieval, which also suggest that the bias-correction scheme implemented may need to be improved."

Suggested technical corrections

L68 Suggest to change "constrain the surface carbon flux inversion" to "constrain the surface carbon fluxes"

Response: We have changed "constrain the surface carbon flux inversion" to "constrain the surface carbon fluxes". See lines 70-71, page 3.

L250 Fprior mistyped

Response: We have corrected "Fpiror" to "Fprior" in the revised manuscript. Seen line 259, page 12.

L256 suggest changing "by multiply by" to "by multiplying by"

Response: We have changed "by multiply by" to "multiplying by" in the revised manuscript. See lines 268-269, page 12.

L276 'In situ' to 'in situ'

Response: We have change "In situ" to "in situ". See line 363, page 17

L377 abbreviated TCCON station names (such as 'Bial') should be explained somewhere in the text.

Response: We have added the full name of TCCON stations in section 2.2 in the revised manuscript. See lines 149-151, page 7.

L392 in "0.34 to0.59" space is missing

Response: We have added space. See line 485, page 25.

L408 in "0.93ppm" space is missing

Response: We have added space. See line 286, page 13.

L415 Instead of Figure 7, Figure 6 should be referred here, as comparisons to TCCON is on Line 447.

Response: We have corrected "Figure 7" to "Figure 4" since according to another referee's comments, the section 4 has been reorganized in the revised manuscript, and Figure 6 is renamed to Figure 4. See lines 345-346, page 16.

Referee #2:

We thank the anonymous referee for his/her valuable comments and constructive suggestions. 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: I was pleased to receive the response of the authors to my comments, and I appreciate the extra effort that was done to address my concerns. I think the manuscript has improved substantially in this revision, but not yet enough for publication in ACP. The manuscript needs quite a few small modifications of errors, typos, and mistakes in at least one figure. It can also profit from rewriting and reordering parts of the text. And before publication can proceed, the authors need to consider the terms of use of the ObsPack data that they downloaded, as currently they did not comply with them. Please find below my additional comments on the new manuscript presented.

Response: We are very grateful to the referee's insightful comments and really appreciate his/her patience while we were working on the manuscript. In the revised manuscript, we have reorganized the section 4. We present the evaluation results first and then followed by the flux analysis. For better clarity, we rewrite the abstract, part of section 4 and conclusions as well. We corrected the mistake in the Figure 4. We also checked errors and typos carefully and made the necessary corrections. We will explain how we follow the terms of use of the ObsPack data in detail.

Main comments:

The use of the ObsPack instead of the flasks is in principle a good idea. I do not understand why the authors decided to download a carbontracker obspack though, as the website that explains this product (https://www.esrl.noaa.gov/gmd/ccgg/obspack/release_notes.html#obspack_co2_1_CARBONTRACKER) explicitly suggests not to use these files as primary source of data for inversions, but instead to get the latest real obspack from the website. It also reminds the user explicitly to comply with the terms of use of these data in a study, which means that (1) all data providers need to be contacted before publication to explain the use of their data and to agree on the way to acknowledge them, (2) a citation to the dataset through its DOI must be included in the text. I repeated this Fair Use Statement in my comments below. Without complying with these rules, the current manuscript should not be published.

Response: Many Thanks for this comment and suggestion. The reason for using CarbonTracker Obspack other than the full ObsPack data is just for convenience. Before we decided to use CarbonTracker ObsPack data, we did read the release note carefully and understand the suggestions for not using those data as primary source for inversions. The latest real ObsPack data contain much more measurements than those used by CarbonTacker. We don't have much experience with assimilating in situ measurements. It is a lot of works to filter out the measurements not suitable for assimilation. It is also not an easy task for us to figure out the appropriate observation uncertainties. Therefore, in order to finish the in situ inversion and complete the revision of the manuscript on time, we chose to use CarbonTracker Obspack data to do the inversion.

We did follow the terms of use of OpsPack data closely. After we downloaded the ObsPack data, we read the terms of use carefully and emailed to all ObsPack PIs to acknowledge the use of data and inquire the proper citation of ObsPack data. We got replies from Dr. Andres Schmidt and Dr. Andy Jacobson and they agreed to let us use the data. All the other PIs didn't reply to us and so we assumed no objections from them for using the data. A copy of email we sent and the replies from Dr. Andres Schmidt and Dr. Andy Jacobson are listed as follows.

(1) Email we sent to all data providers on Apr 7, 2019:

acknowledgement of using obspack_co2_1_CARBONTRACKER_CT2016_2017-02-06 data

发件人：wanghm<wanghm@nju.edu.cn>
时　间：2019年4月7日(星期天) 凌晨0:23
收件人：bev.law<bev.law@oregonstate.edu>; Casper.Labuschagne<Casper.Labuschagne@weathersa.co.za>;
h.a.scheeren<h.a.scheeren@rug.nl>; swofsy<swofsy@seas.harvard.edu>; vandenbulk<vandenbulk@ecn.nl>;
colm.sweeney<colm.sweeney@noaa.gov>; leuenberger<leuenberger@climate.unibe.ch>;
wpaplawsky<wpaplawsky@ucsd.edu>; john.mund<john.mund@noaa.gov>; haszpra.l<haszpra.l@met.hu>;
pshepson<pshepson@purdue.edu>; lukasz.chmura<lukasz.chmura@fis.agh.edu.pl>; necki<necki@agh.edu.pl>;
Gordon.Brailsford<Gordon.Brailsford@niwa.co.nz>; vandinther<vandinther@ecn.nl>;
frank.meinhardt<frank.meinhardt@uba.de>; josep-anton.morgui<josep-anton.morgui@ic3.cat>;
Paul.Steele<Paul.Steele@csiro.au>; anna.karion<anna.karion@noaa.gov>;
marc.delmotte<marc.delmotte@lsce.ipsl.fr>; huilin.chen<huilin.chen@rug.nl>; e.gloor<e.gloor@leeds.ac.uk>;
scpiper<scpiper@ucsd.edu>; Doug.Worthy<Doug.Worthy@ec.gc.ca>; kenneth.c.aikin<kenneth.c.aikin@noaa.gov>;
arlyn.andrews<arlyn.andrews@noaa.gov>; pieter.tans<pieter.tans@noaa.gov>; jeff.peischl<jeff.peischl@noaa.gov>;
Paul.Krummel<Paul.Krummel@csiro.au>; francesco.apadula<francesco.apadula@rse-web.it>;
accox<accox@ucsd.edu>; lvgatti<lvgatti@ipen.br>; Ray.Langenfelds<Ray.Langenfelds@csiro.au>;
ingrid.vanderlaan<ingrid.vanderlaan@wur.nl>; am12721<am12721@bristol.ac.uk>;
Marcel.vanderSchoot<Marcel.vanderSchoot@csiro.au>; petri.keronen<petri.keronen@helsinki.fi>;
roger.curcoll<roger.curcoll@ic3.cat>; sjwalker<sjwalker@ucsd.edu>; zimnoch<zimnoch@agh.edu.pl>;
olli.peltola<olli.peltola@helsinki.fi>; meelis.molder<meelis.molder@nateko.lu.se>;
s.odoherty<s.odoherty@bristol.ac.uk>; MSTorn<MSTorn@lbl.gov>; SCBiraud<SCBiraud@lbl.gov>;
Michel.Ramonet<Michel.Ramonet@lsce.ipsl.fr>; Andres.Schmidt<Andres.Schmidt@oregonstate.edu>;
abollenbacher<abollenbacher@ucsd.edu>; mon<mon@m.tohoku.ac.jp>; ghg_obs<ghg_obs@met.kishou.go.jp>;
janne.levula<janne.levula@helsinki.fi>; Michal.Heliasz<Michal.Heliasz@cec.lu.se>;
Eric.J.Hintsa<Eric.J.Hintsa@noaa.gov>; h.a.j.meijer<h.a.j.meijer@rug.nl>;
michal.galkowski<michal.galkowski@agh.edu.pl>; kenneth.schuldt<kenneth.schuldt@noaa.gov>;
ingeborg.levin<ingeborg.levin@iup.uni-heidelberg.de>; tuula.aalto<tuula.aalto@fmi.fi>; clm<clm@nilu.no>;
thomas.b.ryerson<thomas.b.ryerson@noaa.gov>; oh<oh@nilu.no>;
samuel.hammer<samuel.hammer@iup.uni-heidelberg.de>; hensen<hensen@ecn.nl>;
ed.dlugokencky<ed.dlugokencky@noaa.gov>; frumau<frumau@ecn.nl>; andrew.uea<andrew.uea@gmail.com>;
marcus.schumacher<marcus.schumacher@dwd.de>; kirk.w.thoning<kirk.w.thoning@noaa.gov>;
kathryn.mckain<kathryn.mckain@noaa.gov>; MLFischer<MLFischer@lbl.gov>;
Sylvia.Nichol<Sylvia.Nichol@niwa.co.nz>; g.forster<g.forster@uea.ac.uk>; fred.moore<fred.moore@noaa.gov>;
aoki<aoki@m.tohoku.ac.jp>; alex.vermeulen<alex.vermeulen@nateko.lu.se>;
martin.steinbacher<martin.steinbacher@empa.ch>; stephens<stephens@ucar.edu>;
pasi.kolari<pasi.kolari@helsinki.fi>; nakazawa<nakazawa@m.tohoku.ac.jp>; agomezp<agomezp@aemet.es>;
James.W.Elkins<James.W.Elkins@noaa.gov>; safshar<safshar@ucsd.edu>; rkeeling<rkeeling@ucsd.edu>;
john.b.miller<john.b.miller@noaa.gov>; j.turnbull<j.turnbull@gns.cri.nz>; juha.hatakka<juha.hatakka@fmi.fi>;
yniwa<yniwa@mri-jma.go.jp>; ysawa<ysawa@mri-jma.go.jp>; tmachida<tmachida@nies.go.jp>;
hmatsued<hmatsued@mri-jma.go.jp>; andy.jacobson<andy.jacobson@noaa.gov>

Dear Obspack data providers:

We are preparing a manuscript already posted as discussion paper in ACP, tilted " Differences of the inverted terrestrial ecosystem carbon flux between using GOSAT and OCO-2 XCO2 retrievals"(acp-2018-1175). It is currently under the review stage. Upon the request of reviewers, we need to use in-situ data from "obspack_co2_1_CARBONTRACKER_CT2016_2017-02-06" dataset to do the inversion of surface carbon flux and also to evaluate our inversion results from satellite retrievals. Since it is our first time to use OBSPACK data, please let us know how we can follow the data use policy properly. We would like to know how to cite this dataset since the citation is not sent to us. Do we need to provide reference for every dataset? If so, would data providers please kindly send us the reference of your dataset? If there is any concern on our use of this dataset, please just let us know. Many thanks!

Best regards,

Hengmao Wang
Associate Professor
International Institute of Earth System Science
Nanjing University

(2) The reply from Dr. Andy Jacobson on Apr 7, 2019

Re: acknowledgement of using obspack_co2_1_CARBONTRACKER_CT2016_2017-02-06 data

发件人：Andy Jacobson<andy.jacobson@noaa.gov>
时　间：2019年4月7日(星期天) 凌晨1:22
收件人：wanghm<wanghm@nju.edu.cn>; bev.law<bev.law@oregonstate.edu>;
Casper.Labuschagne<Casper.Labuschagne@weathersa.co.za>; h.a.scheeren<h.a.scheeren@rug.nl>;
swofsy<swofsy@seas.harvard.edu>; vandenbulk<vandenbulk@ecn.nl>; colm.sweeney<colm.sweeney@noaa.gov>;
leuenberger<leuenberger@climate.unibe.ch>; wpaplawsky<wpaplawsky@ucsd.edu>;
john.mund<john.mund@noaa.gov>; haszpra.l<haszpra.l@met.hu>; pshepson<pshepson@purdue.edu>;
lukasz.chmura<lukasz.chmura@fis.agh.edu.pl>; necki<necki@agh.edu.pl>;
Gordon.Brailsford<Gordon.Brailsford@niwa.co.nz>; vandinther<vandinther@ecn.nl>;
frank.meinhardt<frank.meinhardt@uba.de>; josep-anton.morgui<josep-anton.morgui@ic3.cat>;
Paul.Steele<Paul.Steele@csiro.au>; anna.karion<anna.karion@noaa.gov>;
marc.delmotte<marc.delmotte@lsce.ipsl.fr>; huilin.chen<huilin.chen@rug.nl>; e.gloor<e.gloor@leeds.ac.uk>;
scpiper<scpiper@ucsd.edu>; Doug.Worthy<Doug.Worthy@ec.gc.ca>; kenneth.c.aikin<kenneth.c.aikin@noaa.gov>;
arlyn.andrews<arlyn.andrews@noaa.gov>; pieter.tans<pieter.tans@noaa.gov>; jeff.peischl<jeff.peischl@noaa.gov>;
Paul.Krummel<Paul.Krummel@csiro.au>; francesco.apadula<francesco.apadula@rse-web.it>;
accox<accox@ucsd.edu>; lvgatti<lvgatti@ipen.br>; Ray.Langenfelds<Ray.Langenfelds@csiro.au>;
ingrid.vanderlaan<ingrid.vanderlaan@wur.nl>; am12721<am12721@bristol.ac.uk>;
Marcel.vanderSchoot<Marcel.vanderSchoot@csiro.au>; petri.keronen<petri.keronen@helsinki.fi>;
roger.curcoll<roger.curcoll@ic3.cat>; sjwalker<sjwalker@ucsd.edu>; zimnoch<zimnoch@agh.edu.pl>;
olli.peltola<olli.peltola@helsinki.fi>; meelis.molder<meelis.molder@nateko.lu.se>;
s.odoherty<s.odoherty@bristol.ac.uk>; MSTorn<MSTorn@lbl.gov>; SCBiraud<SCBiraud@lbl.gov>;
Michel.Ramonet<Michel.Ramonet@lsce.ipsl.fr>; Andres.Schmidt<Andres.Schmidt@oregonstate.edu>;
abollenbacher<abollenbacher@ucsd.edu>; mon<mon@m.tohoku.ac.jp>; ghg_obs<ghg_obs@met.kishou.go.jp>;
janne.levula<janne.levula@helsinki.fi>; Michal.Heliasz<Michal.Heliasz@cec.lu.se>;
Eric.J.Hintsa<Eric.J.Hintsa@noaa.gov>; h.a.j.meijer<h.a.j.meijer@rug.nl>;
michal.galkowski<michal.galkowski@agh.edu.pl>; kenneth.schuldt<kenneth.schuldt@noaa.gov>;
ingeborg.levin<ingeborg.levin@iup.uni-heidelberg.de>; tuula.aalto<tuula.aalto@fmi.fi>; clm<clm@nilu.no>;
thomas.b.ryerson<thomas.b.ryerson@noaa.gov>; oh<oh@nilu.no>;
samuel.hammer<samuel.hammer@iup.uni-heidelberg.de>; hensen<hensen@ecn.nl>;
ed.dlugokencky<ed.dlugokencky@noaa.gov>; frumau<frumau@ecn.nl>; andrew.uea<andrew.uea@gmail.com>;
marcus.schumacher<marcus.schumacher@dwd.de>; kirk.w.thoning<kirk.w.thoning@noaa.gov>;
kathryn.mckain<kathryn.mckain@noaa.gov>; MLFischer<MLFischer@lbl.gov>;
Sylvia.Nichol<Sylvia.Nichol@niwa.co.nz>; g.forster<g.forster@uea.ac.uk>; fred.moore<fred.moore@noaa.gov>;
aoki<aoki@m.tohoku.ac.jp>; alex.vermeulen<alex.vermeulen@nateko.lu.se>;
martin.steinbacher<martin.steinbacher@empa.ch>; stephens<stephens@ucar.edu>;
pasi.kolari<pasi.kolari@helsinki.fi>; nakazawa<nakazawa@m.tohoku.ac.jp>; agomezp<agomezp@aemet.es>;
James.W.Elkins<James.W.Elkins@noaa.gov>; safshar<safshar@ucsd.edu>; rkeeling<rkeeling@ucsd.edu>;
john.b.miller<john.b.miller@noaa.gov>; j.turnbull<j.turnbull@gns.cri.nz>; juha.hatakka<juha.hatakka@fmi.fi>;
yniwa<yniwa@mri-jma.go.jp>; ysawa<ysawa@mri-jma.go.jp>; tmachida<tmachida@nies.go.jp>;
hmatsued<hmatsued@mri-jma.go.jp>

Dear Dr Wang,

Apologies to all for cross-posting.

You can read about the usage terms for all of our ObsPack products at https://www.esrl.noaa.gov/gmd/ccgg/obspack/. At that site, you will find explicit instructions for how to cite the products and how to acknowledge data providers who have contributed measurements to the products. If you have further questions along those lines, please send them to me and Ken Schuldt (kenneth.schuldt@noaa.gov).

One important aspect of the terms of use for ObsPack products is that you may need to invite data providers to be coauthors on your paper. This depends on how the measurements are used in your paper, and is a conversation you need to have with each data provider. Thank you for starting this process.

The CarbonTracker ObsPack is not the one I would recommend for inversion studies or evaluation. Instead, the GLOBALVIEW+ CO2 ObsPack, currently at version 4.2, is the preferred product for finding the measurements you need. You can use a CarbonTracker ObsPack (although you should instead use the more recent CT2017 one), but that is an indirect way of gaining access to the measurements. GLOBALVIEW+, on the other hand, is produced specifically for the purposes you cite.

I have read your manuscript and I do not need to be a coauthor on it. I agree that your OCO-2 and GOSAT results will be easier to interpret if you also have an inversion using in situ CO2 measurements using your system. You should definitely consider comparing your results to the more recent CT2017 instead of CT2016, as our system has been significantly improved. I ask that you follow our usage terms laid out at https://www.esrl.noaa.gov/gmd/ccgg/carbontracker/citation.php, which in this case would involve an edit on line 26 to correctly identify "NOAA's CarbonTracker, version CT2016", and to add our requested acknowledgments text to your acknowledgments section.

Best Regards,

Andy Jacobson

On 4/6/19 10:23 AM, wanghm wrote:
> Dear Obspack data providers:
>

(3) The reply from Dr. Andres Schmidt on Apr 8, 2019

using obspack_co2_1_CARBONTRACKER_CT2016_2017-02-06 data

发件人：Andres Schmidt<andres.schmidt.osu@gmail.com>
时　间：2019年4月8日(星期一) 上午10:16
收件人：wanghm<wanghm@nju.edu.cn>
抄　送：andres.schmidt<andres.schmidt@oregonstate.edu>; andres.schmidt<andres.schmidt@geo.rwth-aachen.de>

Dear Hengmao Wang,

as far as I am concerned I am happy to see that the data from the carbontracker/obspack sites I am associated with (andres.schmidt@oregonstate.edu)are being used in your manuscript.

Sincerely,

Andres Schmidt
Dept. of Forest Ecosystems & Society
Oregon State University
Cirvallus, OR, USA
(now at RWTH Aachen andres.schmidt@geo.rwth-aachen.de)

We are preparing a manuscript already posted as discussion paper in ACP, tilted " Differences of the inverted terrestrial ecosystem carbon flux between using GOSAT and OCO-2 XCO2 retrievals"(acp-2018-1175). It is currently under the review stage. Upon the request of reviewers, we need to use in-situ data from "obspack_co2_1_CARBONTRACKER_CT2016_2017-02-06" dataset to do the inversion of surface carbon flux and also to evaluate our inversion results from satellite retrievals. Since it is our first time to use OBSPACK data, please let us know how we can follow the data use policy properly. We would like to know how to cite this dataset since the citation is not sent to us. Do we need to provide reference for every dataset? If so, would data providers please kindly send us the reference of your dataset? If there is any concern on our use of this dataset, please just let us know. Many thanks!

Best regards,

Hengmao Wang
Associate Professor
International Institute of Earth System Science
Nanjing University

Although I like the introduction of the poor-man's inversion, the description in the methods section seems incorrect to me, and I find the way it is integrated into the study not very strong. This comes from the choice to use it as an extra inverse solution from the beginning, and to discuss its flux results alongside that of the other inversions. But the poor-man's inversion can only be used to look at the global total flux (which it matches by design), and to look at the distribution of CO_2 mixing ratios and XCO2 values across the globe. This it should follow reasonably well, thus setting a benchmark to beat for real inverse solutions. Currently, the label "benchmark" is used throughout the text including that of "benchmark inversion" which is confusing: the flux result of this poor-man's method is the one thing one should *not* put much emphasis on, especially not below the global total scale. It is therefore also no use to show its regional flux solution in Table 2 and in Fig 4, nor be discussed in Section 4.2 in my opinion.

Response: Thank you for this comment and suggestion. The poor-man inversion conducted in this study was exactly according to the Chevallier's approach. The description of the method was combined from the descriptions of Chevallier et al. (2009) and Chevallier et al. (2010). The difference between Chevallier's approach and ours is that to be consistent with our three other inversions, we set prior flux uncertainty proportional to prior flux in poor-man inversion, while in Chevallier et al. (2010), it was set proportional to the heterotrophic respiration flux of ORCHIDEE, and in Chevallier et al. (2009), it was set prior flux uncertainty proportional to the gross carbon fluxes.

However, we agree with the referee that the way of integrating poor-man inversion into this study is not strong. In the revised manuscript, we have changed all "benchmark inversion" to "poor-man inversion", removed poor-man inversion results from Table 2 and Fig 4, and removed the comparisons and discussions of regional carbon fluxes of poor-man inversion result in Section 4.2 in the revised manuscript. It should be noted that since section 4 was reorganized, now, Table 2 and Fig 4 are renamed to Table 3 and Fig 6, and Section 4.2 is renamed as Section 4.3 in the revised manuscript.

It is a bit awkward that the reader is first learning a lot about GoSAT to OCO-2 flux differences and how their regional budgets differ in great detail in Section 4.2, but only later in Section 4.3 learns that the OCO-2 inversion is not very trustworthy and is not able to reproduce the atmospheric XCO2 and surface CO_2 better than the poor-man's inversion (which can be called a benchmark in this context). So in fact, all I read earlier becomes then in a sense irrelevant. Please consider bringing the assessment of the quality of the inversions forward in the manuscript, so that the flux analysis that comes afterwards can focus more on the relevant part of the study (GoSAT and in-situ inverse results). OCO-2 can then be still discussed, but only to indicate whether GoSAT satellite results are corroborated or not by OCO-2.

Response: Thanks for the referee's suggestion. In the revised manuscript, we have reorganized Section 4 and present the assessment of the quality of the inversions first in Section 4.1, and the flux analysis on Global budget and regional fluxes afterward in Section 4.2 and Section 4.3. We also add more analysis about the comparisons between the satellites and in situ inversions as follows, which is shown in lines 409-420, pages 20-21 in the revised manuscript.

"Compared with the in situ inversion, in the boreal regions, the land sinks estimated from GOSAT and OCO-2 inversions are much weaker than those from in situ inversion, especially in the Eurasian Boreal, the land sink estimated by in situ inversion is more than two times larger than the estimates of GOSAT and OCO-2 inversions. In the tropical land, the total land sinks inferred from both GOSAT and OCO-2 inversions are weaker than those from the in situ inversion, but in different regions, the situations are different. In the Temperate lands, except for Europe and south Africa, the land sinks from GOSAT and OCO-2 inversions are much stronger than those from the in situ inversion. For example, in South America Temperate, GOSAT inversion shows a strong carbon sink, while in situ inversion shows a weak source. For different continents, in North America, Asia, Europe, the carbon sinks inferred from GOSAT inversion are comparable to those from in situ inversion, while in South America and Africa, the carbon sinks inferred from OCO-2 inversion are much closer to the in situ inversions."

Abstract: I think that the text does not summarize so well the main findings anymore, and should be rewritten. The main message should focus on the posterior fluxes compared to the in-situ inversion, and not comparing the two satellites to the prior. Then, one can highlight that the main difference on the largest scale is the latitudinal distribution of land sinks, with the satellites suggesting a smaller Boreal and Tropical sink, combined with larger temperate sinks in both the NH and SH. However, OCO-2 and GoSAT generally do not agree on which continent contains the smaller or larger sinks. Also, the comparison of the simulated surface mixing ratios and XCO2 columns shows that only GoSAT and the in-situ inversion perform better than a poor-man's solution that closes the annual global mass balance of CO_2. This puts the usefulness of the OCO-2 retrieval product used here into question.

Response: Many thanks for this suggestion. We have rewritten the abstract. In the revised manuscript, we removed the statement on the differences between posterior fluxes from satellites and prior fluxes and focus more on the comparisons between satellites and in situ inversion. We highlight the following conclusions:

(1) 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 the in situ inversion, and matches the poor-man inversion to be the best.

(2) Regionally, in most regions, the land sinks inferred from GOSAT data are also stronger than those from OCO-2 data, and in North America, Asia, Europe, the carbon sinks inferred from GOSAT inversion are comparable to those from in situ inversion. For the latitudinal distribution of land sinks, the satellites-based inversions suggest a smaller bo-real and tropical sink, but larger temperate sinks in both Northern and Southern Hemispheres than the in situ inversion. However, OCO-2 and GOSAT generally do not agree on which continent contains the smaller or larger sinks.

(3) Evaluations using flask and TCCON observations and the comparisons with in situ and poor-man inversions suggest that only GOSAT and the in situ inversions perform better than a poor-man's solution. GOSAT data can effectively improve the carbon flux estimates in Northern Hemisphere, while OCO-2 data, with the specific version used in this study, shows only slight improvement.

For details, please refer to lines 15-17, lines 20-22, lines 24-32, pages 1-2.

List of remarks:

page 1, line 15 "benchmark inversion": I would refer to the latter as a poor-man's inversion in which only the global CO_2 growth rate is projected onto the land biosphere, to be used as a benchmark for the simulated atmospheric CO_2 distributions of the real inversions.

Response: We have changed "benchmark inversion" to "poor-man inversion" and rephrase the sentence as "One inversion for the comparison, using in situ CO_2 observations, and another inversion as a benchmark for the simulated atmospheric CO_2 distributions of the real inversions, using global atmospheric CO_2 trend and referred as poor-man inversion, are also conducted."

For details, please refer to lines 15-17, page 1**.**

page 1, line 22: "more consistent with …" simply say that the GoSAT-based inversion seems to best capture the observed global CO_2 growth rate.

Response: We have rephrased that sentence as "…estimated from GOSAT data is stronger than that inferred from OCO-2 data, weaker than the in situ inversion, and matches the poor man inversion to be the best." See lines 21-22, page 1.

Page 2, line 29: it is worth to say explicitly that the OCO-2 retrieval you used here seems unfit for inverse modeling, but that later versions seem to perform better (Chevallier et al., 2019, ACPD). I also urge the authors to focus their future efforts on the later retrieval products from OCO-2.

Response: We have added one sentence "OCO-2 data, with the specific version used in this study, show only slight improvement" (see lines 31-32, page 2) to point out the poor performance of OCO-2 product used in this study. We also mention in the end of conclusion section that the improved performance of newer version of OCO-2 product. "... It also should be noted that though the OCO-2 XCO_2 retrievals of version b7.3 used in this study perform worse than GOSAT data and in situ measurements in our inversions, one recent study has shown that the newer version of OCO-2 data has a much better performance in constraining carbon flux (Cheval-lier et al., 2019). With constantly improved retrieval algorithm and bias-correction scheme, more robust estimate of carbon flux from satellite XCO2 retrievals could be achieved."

For details, see lines 31-32, page 2, and lines 528-533, page 26.

Page 4, line 84: please do not use "benchmark inversion" to label this flux product, but explain the purpose of this approach better.

Response: We have changed all "benchmark inversion" to "poor-man inversion" and given more explanation on the purpose of using poor-man inversion.

"For comparisons, one inversion based on in situ measurements is conducted, and another simple one, which uses the global CO_2 trend as a benchmark for the simulated atmospheric CO_2 distributions of the real inversion, is also implemented."

See lines 86-88, page 4.

Page 6, line 128: This is where my main comment comes into play. The Fair Use Statement given in the readme file of the Obspack you downloaded was:

ObsPack Fair Use Statement

#

This cooperative data product is made freely available to the scientific community and is intended to stimulate and support carbon cycle modeling studies. We rely on the ethics and integrity of the user to assure that each contributing national and university laboratory receives fair credit for their work. Fair credit will depend on the nature of the work and the requirements of the institutions involved.

Your use of this data product implies an agreement to contact each contributing laboratory for data sets used to discuss the nature of the work and the appropriate level of acknowledgement. If this product is essential to the work, or if an important result or conclusion depends on this product, co-authorship may be appropriate. This should be discussed with the appropriate data providers at an early stage in the work. Contacting the data providers is not optional; if you use this data product, you must contact the applicable data providers. To help you meet your obligation, the data product includes an e-mail distribution list of all data providers.

This data product must be obtained directly from the ObsPack Data Portal at www.esrl.noaa.gov/gmd/ccgg/obspack/ and may not be re-distributed. In addition to the conditions of fair use as stated above, users must also include the ObsPack product citation in any publication or presentation using the product. The required citation is included in every data product and in the automated e-mail sent to the user during product download.

Response: As answered in the major comments part, we paid close attention to the fair use of data and followed the terms of use of data as required.

Page 7, line 147: insert "area" between shaded and shows

Response: We have inserted "area". See line 156, page 8.

Page 9, line 196: This is yet another reference "CO_2 trend" to the poor-man's inversion. Pleas try to introduce it better, and use it consistently please.

Response: We have rephrased the sentence as follow: "Three inversions, using GOSAT data, OCO-2 data, and in-situ measurements, are conducted from Oct 1, 2014 to December 31, 2015, respectively. Poor-man inversion, based on global atmospheric CO_2 trend and using poor-man's method (Chevallier et al, 2009, 2010), is also conducted." in the revised manuscript. See lines 204-207, page 10.

Page 11, line 232: descripted = described

Response: We have corrected "descripted" to "described". See Line 242, page 11.

Page 12, line 249: I do not understand this formula and I wonder if a mistake was made. piror = prior (typo). But why do you add something proportional to the prior flux uncertainty, instead of proportional to GPP? And why do you need trial-and-error to determine the scaling factor k? This is not the same approach as taken by Chevallier, whom you cite for this approach.

Response: Thank you for this comment.

(1) Yes, "piror" is a typo, we have corrected "piror" to "prior". See line 259, page 12

in the revised manuscript.

(2) The poor-man inversion conducted in this study was exactly according to the Chevallier's approach. In the introduction of this method, we combined the descriptions from Chevallier et al. (2009) and Chevallier et al. (2010).

In the page 4 of Chevallier et al. (2009), the method is described as follows:

"…The ocean fluxes are kept identical, to the prior ones. Over land, the inverted fluxes $\mathbf{x}_{\mathbf{pm}}$ are defined as

$$x_{pm} = x_b - k\sigma$$

where k is a unique scaling factor and σ is the vector made of the prior error standard deviations, i.e., the square root of the diagonal of **B**. Here k was chosen by trial and error so that the mean global total of the $\mathbf{x}_{\mathbf{pm}}$ fluxes equals the mean global total of fluxes inverted from the surface measurements over the 3-year period. A value of 1/55 was found. This simple approach aims at matching the mean global growth rate of CO2, which is too large with our prior fluxes over land (see the end of section 2.1.2), without any spatial or temporal information from the observations. In practice, it distributes the land carbon sink according to the gross carbon fluxes from the vegetation.".

In the page 8 of Chevallier et al. (2010), it was described as follow:

"…In this baseline (which is slightly simplified here), the ocean fluxes are kept identical to the prior ones. Over land the poor man's flux *F*pm at location (*x*, *y*) and at time *t* is defined as

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

$F_{prior}(x, y, t)$ is the prior flux at the same time and location. $\sigma(x,y,t)$ is its uncertainty, that is, the standard deviation of the prior error described in section 2.1. *k(year)* is a coefficient that varies as a function of the year only. *k* is chosen here so that the mean annual global totals of the poor man's fluxes equal the mean global totals given by the annual global CO_2 growth rate from the *GLOBALVIEW*-CO_2 [2009] product multiplied by a conversion factor (2.12 GtC a^{-1} per ppm [Denman et al., 2007, Table 7.1]), In practice, this simple approach distributes the land carbon sink according to the heterotrophic respiration fluxes from the vegetation without any spatial information from the atmospheric observations or any temporal information within any given year.”.

In these two papers, σ was explicitly defined as prior flux uncertainty. The difference between their approach and ours is that to be consistent with our three other inversions, we set prior flux uncertainty proportional to prior flux in poor-man inversion, while in Chevallier et al. (2010), it was set proportional to the heterotrophic respiration flux of ORCHIDEE, and in Chevallier et al. (2009), it was set prior flux uncertainty proportional to the gross carbon fluxes.

For the calculation of the coefficient of k, we agree the referee that we don’t need to do trial-and-error to determine it, k can be solved directly from the formula as

$$k = \left(\sum F_{pm} - \sum F_{prior}\right) / \sum \sigma \quad (1)$$

Where $\sum F_{pm}$ equals the global totals given by the observed annual global CO_2 growth rate. During the calculation, since on different time scale, the σ is different and the global annual uncertainty is not simply the summation of each grid per hour, we calculated several times and got different coefficient of k for different time scale. That is why we said that we did trial-and-error to determine k. However, anyway, we found that whatever did we calculate on monthly or annual time scale, the final F_{pm} distributed on each grid and each three hours are the same. Therefore, the statement of “k is determined by trial-and-error” is indeed improper. We have changed this statement in the revised manuscript. For details, please refer to lines 260-265, page 12.

Chevallier, F., Engelen, R. J., Carouge, C., Conway, T. J., Peylin, P., Pickett‐Heaps, C., Ramonet, M., Rayner, P. J., and Xueref-Remy, I.: AIRS‐based versus flask‐based estimation of carbon surface fluxes, J. Geophys. Res., 114, D20303, doi:10.1029/2009JD012311, 2009.

Chevallier, F., Ciais P., Conway T.J., Aalto T., Anderson B.E., Bousquet P., Brunke E.G., Ciattaglia L., Esaki Y., Fröhlich M., Gomez A., Gomez-Pelaez A.J., Haszpra L., Krummel P.B., Langenfelds R.L., Leuenberger M., Machida T., Maignan F., Matsueda H., Morguí J.A., Mukai H., Nakazawa T., Peylin P., Ramonet M., Rivier L., Sawa Y., Schmidt M., Steele L.P., Vay S.A., Vermeulen A.T., Wofsy S., and Worthy D.: CO_2 surface fluxes at grid point scale estimated from a global 21 year reanalysis of atmospheric measurements, J. Geophys. Res., 115, D21307, 2010.

Page 12, line 260: "inverted global carbon budgets" please remove "inverted"

Response: We have removed "inverted". See line 351, page 16.

Page 12, line 263: "benchmark inversion" please rewrite

Response: We have replaced "benchmark inversion" with "poor-man inversion". See line 355, page 17.

Page 16, line 316: In my opinion the benchmark inversion is not very useful here, as its regional flux simply reflects global GPP and not a piece of information derived from the data like in the actual inversions. I suggest to remove it here, and in Fig 4.

Response: Thank you for this suggestion. We have removed results of poor-man inversion in Table 2 and Fig 4 which are now renamed as Table 3 and Fig 6 in the revised manuscript. See lines 404-407, page 20.

Page 17, line 321: "close to the benchmark result": by writing this, you suggest to the reader that it is a good thing for the inversions to be close to the benchmark. But for continental fluxes this is not true at all, and this is why I think this gives the wrong message when put into the figure/text/table.

Response: Thank you for this comment. We have removed the comparison of regional carbon fluxes with "benchmark inversion" in the revised manuscript. Seen lines 409-420, pages 20-21.

Page 20, line 380: Why is this section here, and not part of Section 4.3 where once again a comparison to TCCON is presented? And why are the other two results (in situ and benchmark) not shown? I think it would help to group these results together.

Response: This paragraph only gives comparisons between TCCON XCO_2 retrieval and GOSAT and OCO-2 XCO_2 retrievals. The aim of these comparisons is to show the uncertainties of OCO-2 and GOSAT retrievals, so as to explain the reason for the different performances of OCO-2 and GOSAT retrievals in the inversions. At the beginning of that paragraph, we have emphasized this objective using the sentences of "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 retrieval to evaluate the uncertainties of OCO-2 and GOSAT XCO2 retrievals." (See lines 473-475, page 24). We found that although both OCO-2 and GOSAT products were bias-corrected using TCCON retrieval, there are larger mismatches between OCO-2 and TCCON than those between GOSAT and TCCON, and the mismatches among different sites of GOSAT are more consistent than OCO-2, indicating that the uncertainties of OCO-2 products are larger than GOSAT ones, resulting worse performance of OCO-2 retrieval than that of GOSAT retrieval. The objective of the paragraph is different from those in section 4.3.2, which shows the evaluation of posterior XCO_2 against TCCON data. Therefore, we still don't combine this paragraph with section 4.3.1 in the revised manuscript. However, in order to make it clear, we reorganized part of that paragraph as follows:

"…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, and in the range of 0.34 to 0.59 ppm only at 3 sites. Overall, GOSAT retrievals (-0.46 ppm) have lower bias than OCO-2 retrievals (0.6 ppm) and the difference between two retrievals is relatively large. It should be noted that due to the limited number of collocated satellite retrievals, the real bias difference might not be up to 1 ppm. As shown in Table 4, the difference of overall mis-matches between GOSAT and OCO-2 data is 0.57 ppm. These indicate that although both OCO-2 and GOSAT products were bias-corrected using TCCON retrievals, the uncertainties of OCO-2 and GOSAT retrievals are still very large, especially for OCO-2 retrieval, resulting the worse performance of OCO-2 retrieval, , which also suggest that the bias-correction scheme implemented may need to be improved."

See lines 481-493, pages 24-25.

Page 21, line 392, space missing and typo in “to0.59 pm”

Response: We have added space and corrected the typo. See line 485, page 25.

Page 21, line 409: Please make clear that this is not surprising because part of these evaluation data were used in the inversion in that case

Response: Thank you for this suggestion. We have rewritten the sentence as follows: “Not surprisingly, in situ inversion, using surface observations which include all the flask measurements used for evaluation, shows the best improvement in posterior CO_2 mixing ratio with”

See line 288, page 13.

Page 22, line 426: litter = little

Response: We have changed “litter” to “little”. See line 306, page 14.

Page 23, line 436: “ground XCO2 observations”, please simply write “We use data from 13 TCCON sites to…”

Response: We have rewritten the sentence as “We also use data from 13 TCCON sites to…”. See line 317, page 14.

Page 23, line 436: Please make clear that also here the comparison is not fully independent: the TCCON data were used in the bias correction scheme of at least OCO-2 (I don’t know about GoSAT but I suspect the same there).

Response: Yes, TCCON data were also used in the bias correction scheme of GOSAT product. We have added a sentence here to point out that the comparison is not fully independent.

“It should be noted that the comparisons of posterior XCO_2 from GOSAT and OCO-2 inversions with TCCON data are not fully independent since the TCCON data were used in the bias-correction scheme of both GOSAT and OCO-2 products (Wunch et al., 2011)."

See Line 320-323, page 15.

Page 23, line 437: into = onto

Response: We have changed "into" to "onto". See line 318, page 14.

Page 24, line 461: The fact that only the in-situ inversion beats the benchmark on all 4 numbers should be mentioned in the text.

Response: Thank you for this suggestion. We have mentioned it as follows, and see lines 339-342, page 15 of the revised manuscript.

"…Overall, it also could be found from Table 1 that only in situ inversion beats the poor-man inversion on all 4 statistics, followed by GOSAT inversion, which beats the poor-man on 3 statistics, indicating that in situ measurements have the best performance in the inversion, and GOSAT retrieval have similar performance as in situ data."

Page 25, Figure 7: There seems to be an error in the figure: the bars for benchmark and in-situ are exactly the same for all sites. Please check and fix this.

Response: Thank you very much! Yes, we made an error in this figure. We have redrawn this figure, in the revised manuscript, it has been renamed as Figure 4. See line 348, page 16.

Page 26, line 490: I would not say that OCO-2 could improve the modeling of CO_2 concentrations: your poor-man's inversion shows that you can achieve better results by simply scaling your fluxes to match the global growth rate of CO_2.

Response: We have rephrased the statement as follow:

"Evaluations of the inversions using CO_2 concentrations from flask measurements and TCCON retrievals show that the simulated CO_2 concentrations with GOSAT posterior fluxes are much closer to the observations than those with OCO-2 estimates…."

For details, see Line 515-523, page 27.

Page 26, line 492: "bench inversion" incorrect

Response: We have replaced "bench inversion" with "poor-man inversion". See line 520, page 27.

Page 26, line 495 "GOAST" typo

Response: We have corrected "GOAST" to "GOSAT". See line 520, page 27.

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. One inversion for the comparison, using in situ CO_2 observations, and another inversion as a benchmark for the simulated atmospheric CO_2 distributions of the real inversions, using global atmospheric CO_2 trend and referred as poor-man inversion, 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. Globally, the terrestrial ecosystem carbon sink (excluding biomass burning emissions) estimated from GOSAT data is stronger than that inferred from OCO-2 data, weaker than the in situ inversion, and matches the poor-man inversion to be the best. Regionally, in most regions, the land sinks inferred from GOSAT data are also stronger than those from OCO-2 data, and in North America, Asia, Europe, the carbon sinks inferred from GOSAT inversion are comparable to those from in situ inversion. For the latitudinal distribution of land sinks, the satellites-based inversions suggest a smaller boreal and tropical sink, but larger temperate sinks in both Northern and Southern Hemispheres than the in situ inversion. However, OCO-2 and GOSAT gen-

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

erally do not agree on which continent contains the smaller or larger sinks. Evaluations using flask and TCCON observations and the comparisons with in situ and poor-man inversions suggest that only GOSAT and the in situ inversions perform better than a poor-man's solution. GOSAT data can effectively improve the carbon flux estimates in Northern Hemisphere, while OCO-2 data, with the specific version used in this study, shows only slight improvement. The differences of inferred land fluxes between GOSAT and OCO-2 inversions in different regions are mainly related to the spatial coverage, the data amount, and the biases of these two satellites XCO_2 retrievals.

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 undersampled 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 fluxes (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 and better spatial coverage, current OCO-2 observations have a greater potential than GOSAT observations for estimating CO_2 flux at regional or finer scale, since except spatial coverage, the biases also affect the usefulness of satellite retrievals greatly. 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). For comparisons, one inversion based on in situ measurements is conducted, and another simple one, which uses the global CO_2 trend as a benchmark for the simulated atmospheric CO_2 distributions of the real inversion, is also implemented. For simplicity, four inversions are referred as OCO-2 inversion, GOSAT inversion, in situ inversion and poor-man inversion, respectively. Inversion results are 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, surface observations and the inversion methodology. Inversion settings are described in Section 3. Results and discussions are presented in Section 4, and Conclusions are given in Section 5.

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.

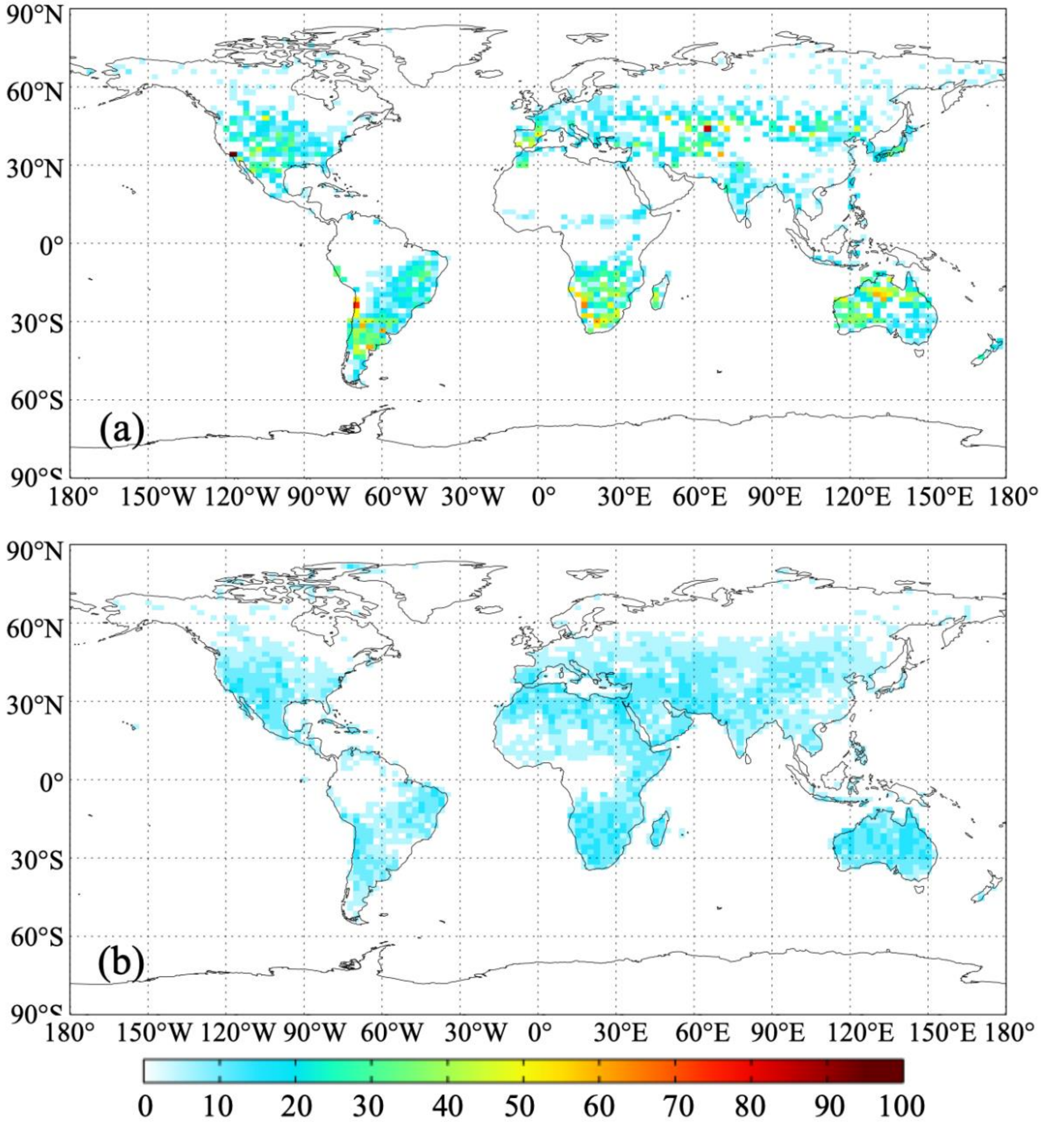

Figure 1. Data amount of each grid cell (2°×2.5°) of ACOS XCO_2 used in this study (a, GOSAT; b, OCO-2)

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://carbontracker.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 4.1.1).

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 names of the 13 stations are Bialystok (Bial), Bremen (Brem), Orleans (Orle), Garmisch (Garm), Darwin (Darw), Izana (Izan), Ny Alesund (Ny_A), Lamont (Lamo), Lauder (Laud), Park Falls (Park), Sodankyla (Soda), Tsukuba (Tsuk), and Wollongong (Woll). The locations of in situ sites and 13 TCCON stations are shown in Figure 2.

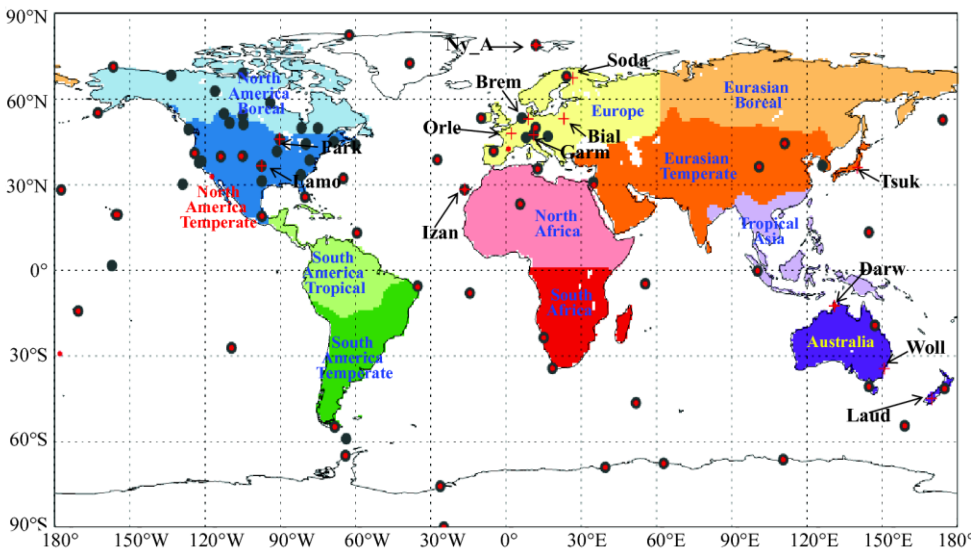

Figure 2. Distributions of the observation sites used in this study. Gray solid circles are surface sites used in the in situ inversion, red points and red cross marks are surface flask and TCCON sites

used for evaluations, respectively, the shaded area 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:

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

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:

$$XCO_2^{m} = XCO_2^{a} + \sum_j h_j a_j (A(x) - y_{a,j}) \quad (2)$$

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. Three inversions, using GOSAT data, OCO-2 data, and in situ measurements, are conducted from Oct 1, 2014 to December 31, 2015, respectively. Poor-man inversion, based on global atmospheric CO_2 trend and using poor-man's method (Chevallier et al, 2009, 2010), is also conducted. 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 described 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 Poor-man inversion

A baseline inversion, which was introduced by Chevallier et al. (2009, 2010) 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:

$$F_{pm}(x,y,t) = F_{prior}(x,y,t) + k \times \sigma(x,y,t) \quad (3)$$

where F_{prior} is the prior flux, σ is the uncertainty of the prior flux, k is a coefficient, it can be solved directly from the formula (3) as

$$k = \left(\sum F_{pm}(x,y,t) - \sum F_{prior}(x,y,t)\right) / \sum \sigma\,(x,y,t) \quad (4)$$

where $\sum F_{pm}(x,y,t)$ equals the global total land flux, which can be calculated from the observed annual global CO_2 growth rate, global annual fossil fuel and biomass burning emissions, and ocean flux. In this study, the observed annual global CO_2 growth rate is 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 multiplying by a factor of 2.123 PgC ppm^{-1}.

4. Results and Discussions

4.1 Evaluation for the inversion results

4.1.1 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 1 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 0.93 ppm, 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 which include all the flask measurements used for evaluation, shows the best improvement in posterior CO_2 mixing ratio with the largest reduction of bias and standard deviation. GOSAT inversion achieves 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. Poor-man inversion effectively reduces the bias but with little improvement in the reduction of standard deviations.

Figure 3 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 little improvement in Southern Hemisphere. Though poor-man inversion effectively reduces the global bias, it shows largest negative biases in Southern Hemisphere and moderate positive biases (close to OCO-2 inversions) in Northern Hemisphere, indicating that the improvements of poor-man inversion for posterior concentrations are very limited. 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.

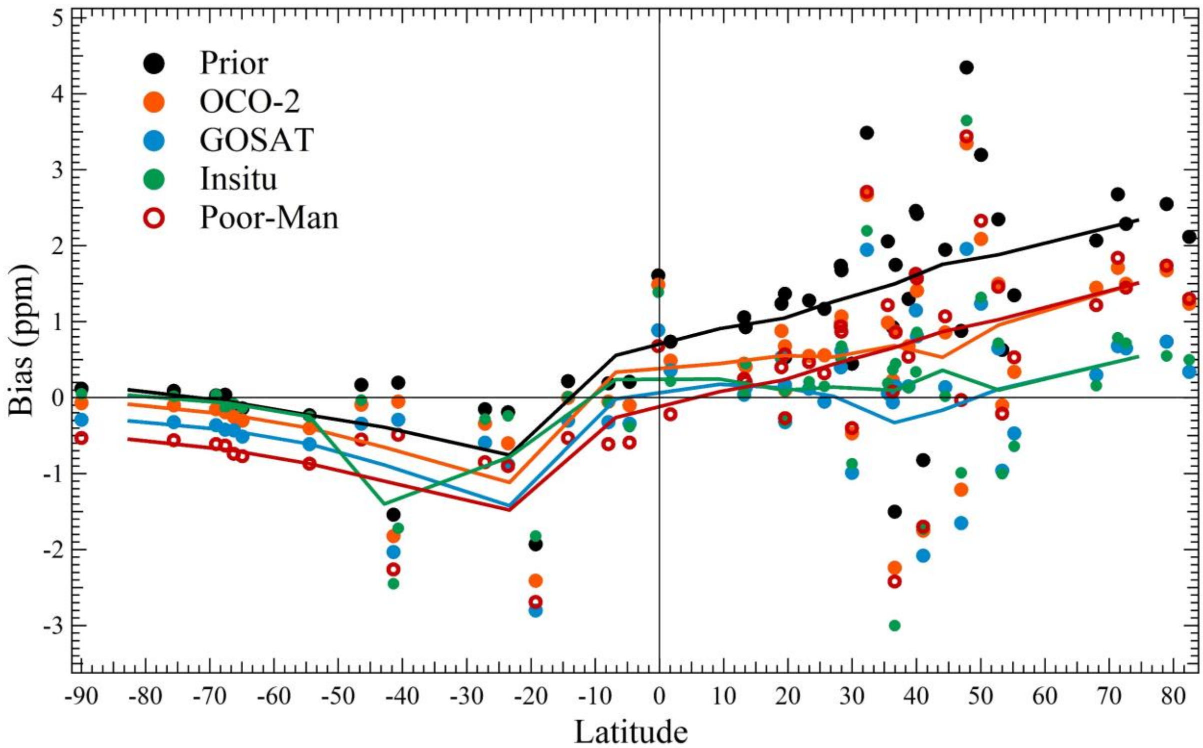

Figure 3. Biases of the simulated CO_2 mixing ratios against the flask measurements in different latitudes (positive/negative biases represent modeled concentration being greater/less than the observed, the different color lines are the smooth of the corresponding marks)

4.1.2 TCCON observations

We also use data from 13 TCCON sites (Figure 2) to evaluate our inversion results. The simulated CO_2 concentrations at 47 vertical levels are mapped onto 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. It should be noted that the comparisons of posterior XCO_2 from GOSAT and OCO-2 inversions with TCCON data are not fully independent since the TCCON data were used in the bias-correction scheme of both GOSAT and OCO-2 products (Wunch et al., 2011). Table 1 also 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 deviation. Though OCO-2 inversion shows improvement in the reduction of standard deviation, it gives a relatively large bias for posterior XCO_2. In situ inversion has the same reduction of standard deviation as GOSAT inversion. Poor-man inversion reduces the bias to 0.49 ppm and gives slight improvement in reducing standard deviation of posterior XCO_2.

Figure 4 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 Lamo site. GOSAT and in situ inversions significantly reduce the biases at most sites. However, in Northern Hemisphere, 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 be also related to the biases of TCCON retrievals (Wunch et al, 2010; Messerschmidt et al, 2011). OCO-2 and poor-man inversions show slight improvement in the reduction of biases at most sites and rather large biases still remain.

Overall, it also could be found from Table 1 that only in situ inversion beats the poor-man inversion on all 4 statistics, followed by GOSAT inversion, which beats the poor-man on 3 statistics, indicating that in situ measurements have the best performance among all inversions, and GOSAT retrieval have similar performance as in situ data.

Table 1. Statistics of the model-data mismatch errors at the 52 surface flask sites and the 13 TCCON sites (ppm)

	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
Poor-man	0.14	2.28	0.49	1.25

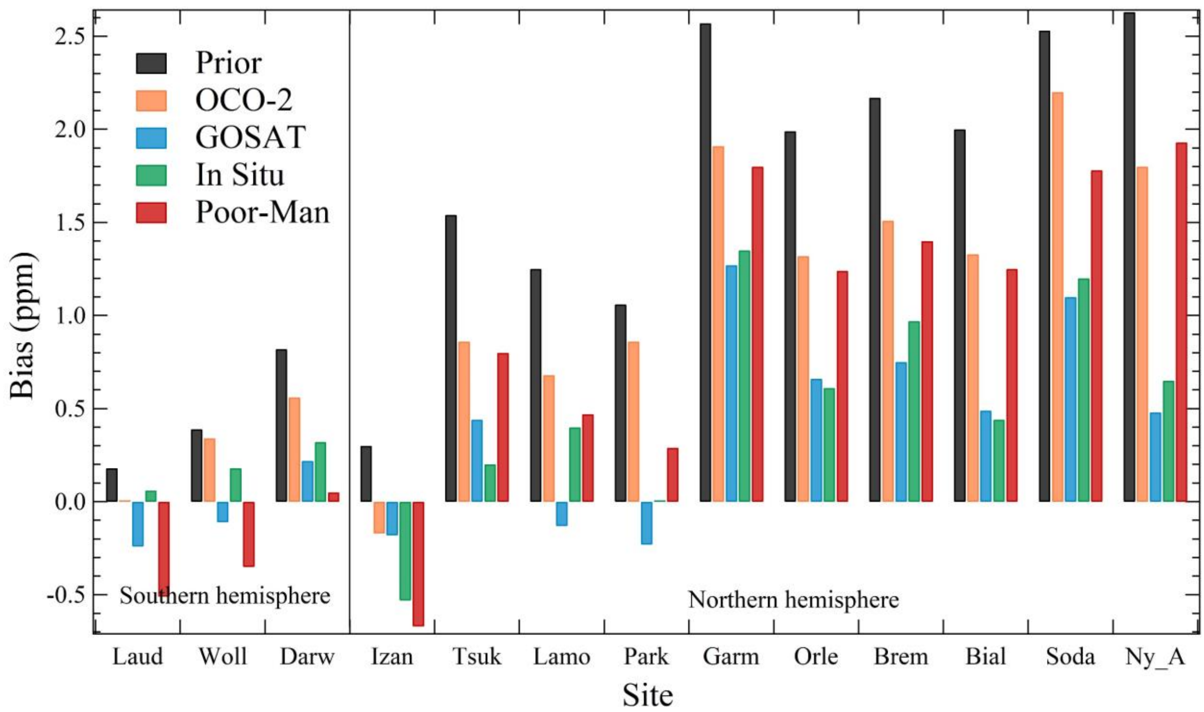

Figure 4. The biases between the modeled and observed XCO_2 at the 13 TCCON sites

4.2 Global carbon budget

Table 2 presents the 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 differences of ocean fluxes among a priori and two inversions are small since we don’t assimilate

XCO_2 data over ocean. The global net flux from the poor-man 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 poor-man inversion estimate, while that from OCO-2 inversion is higher and the in situ inversion estimate is lower than the poor-man estimate, indicating that GOSAT inversion has the best estimates for the land and ocean carbon uptakes, while those from in situ inversion are overestimated, and those from OCO-2 inversion might be underestimated.

Table 2. 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 poor-man inversions (PgC yr^{-1})

	Prior	OCO-2	GOSAT	In situ	Poor-man
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

4.3 Regional carbon flux

Figure 5 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.

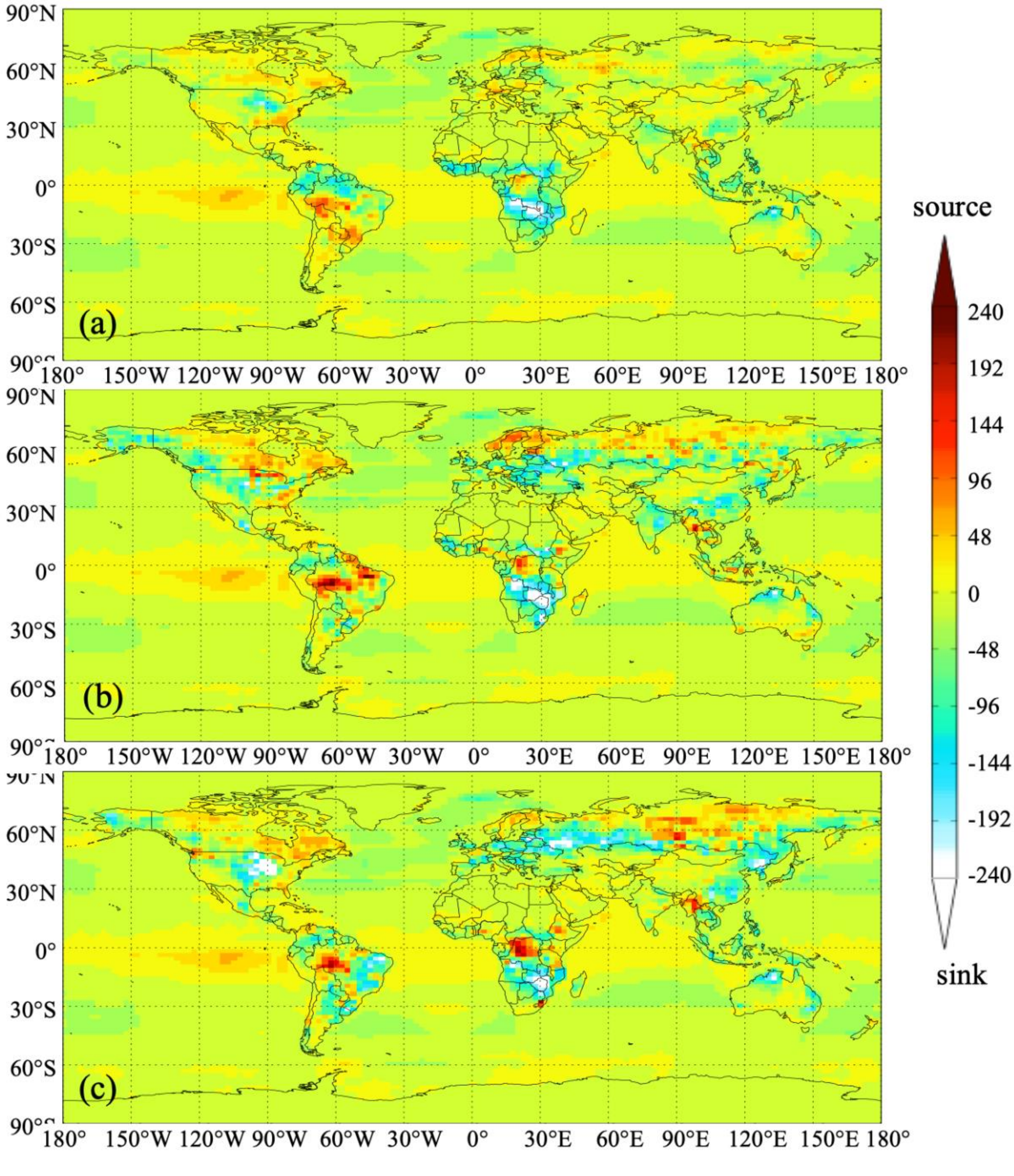

Figure 5. Distributions of annual land and ocean carbon fluxes a) prior flux and posterior fluxes based on (b) OCO-2 and (c) GOSAT data (gC $m^{-2}yr^{-1}$)

To better investigate the differences between GOSAT and OCO-2 inversions as well as their differences with 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 6 shows aggregated annual land surface fluxes from the prior and 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 3). 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 3), 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}).

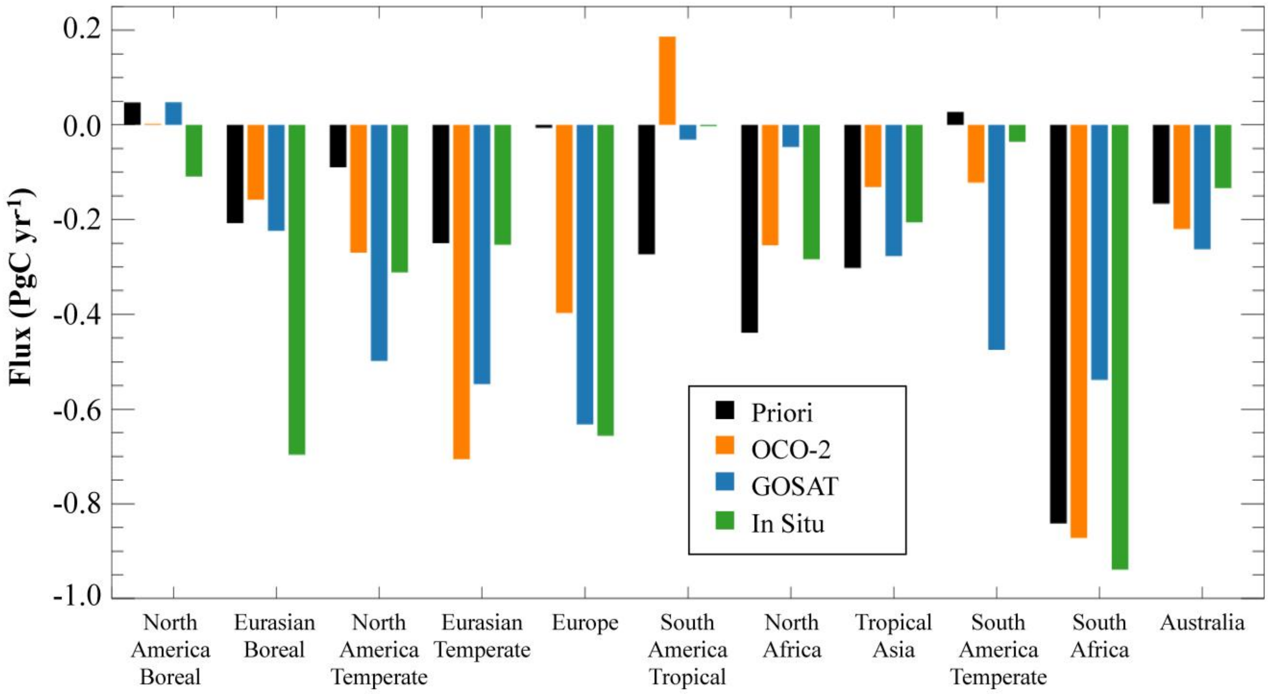

Figure 6. Aggregated annual land fluxes of the 11 TRANSCOM land regions

Table 3. The prior and posterior fluxes in six continents and boreal, temperate and tropical lands (PgC yr^{-1})

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

Compared with the in situ inversion, in the boreal regions, the land sinks estimated from GOSAT and OCO-2 inversions are much weaker than those from in situ inversion, especially in the Eurasian Boreal, the land sink estimated by in situ inversion is more than two times larger than the estimates of GOSAT and OCO-2 inversions. In the tropical land, the total land sinks inferred from both GOSAT and OCO-2 inversions are weaker than those from the in situ inversion, but in different regions, the situations are different. In the Temperate lands, except for Europe and south Africa, the land sinks from GOSAT and OCO-2 inversions are much stronger than those from the in situ inversion. For example, in South America Temperate, GOSAT inversion shows a strong carbon sink, while in situ inversion shows a weak source. For different continents, in North America, Asia, Europe, the carbon sinks inferred from GOSAT inversion are comparable to those from in situ inversion, while in South America and Africa, the carbon sinks inferred from OCO-2 inversion are much closer to the in situ inversion.

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 4, 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 4. 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 XCO_2 with prior flux and satellite retrieved XCO_2

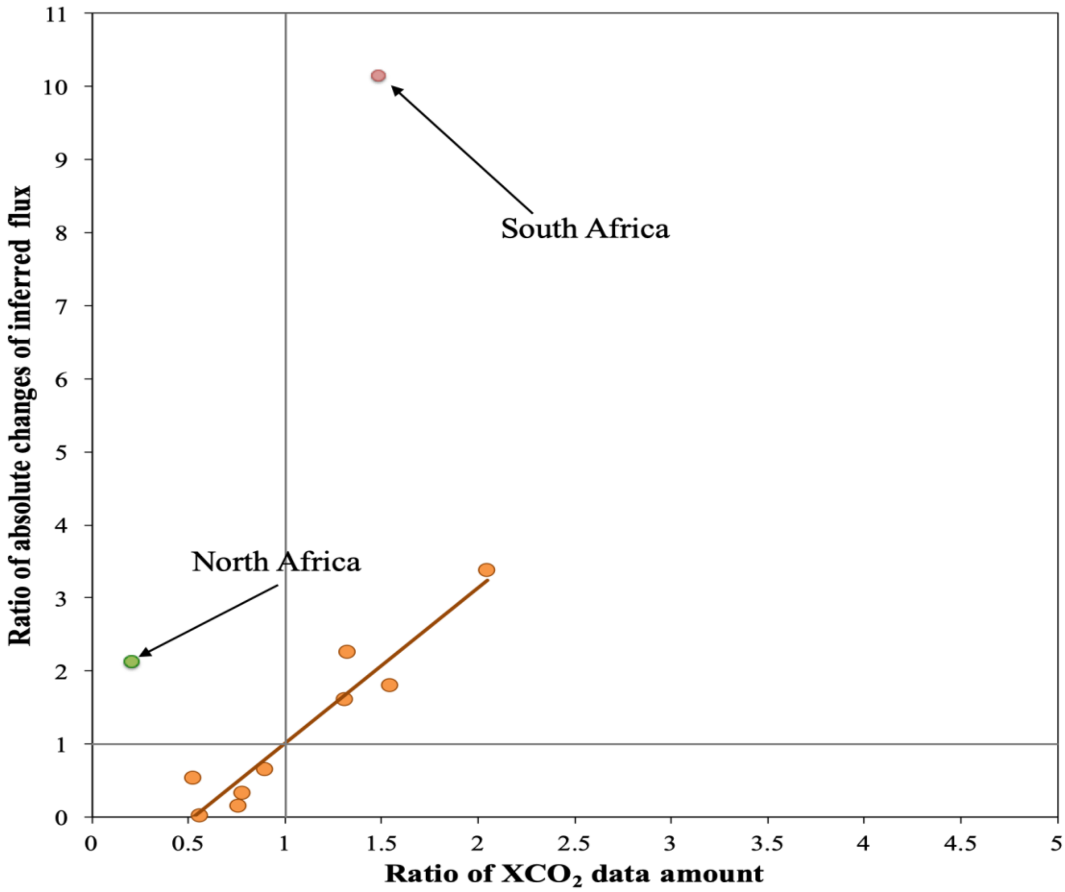

Figure 7. Scatter plot for the ratio of GOSAT to OCO-2 XCO_2 data amount versus the ratio of absolute changes of the land sinks caused by GOSAT to OCO-2 in the 11 TRANSCOM land regions

In addition to the data amount, the mismatches between the simulated CO_2 concentrations using prior fluxes and the satellite retrievals could be used to examine 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 4. 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 5. 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 retrieval 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 5 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. 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, and in the range of 0.34 to 0.59 ppm only at 3 sites. Overall, GOSAT retrievals (-0.46 ppm) have lower bias than OCO-2 retrievals (0.6 ppm) and the difference between two retrievals is relatively large. It should be noted that due to the limited number of collocated satellite retrievals, the real bias difference might not be up to 1 ppm. As shown in Table 4, the difference of overall mismatches between GOSAT and OCO-2 data is 0.57 ppm. These indicate that although both OCO-2 and GOSAT products were bias-corrected using TCCON retrievals, the uncertainties of OCO-2 and GOSAT retrievals are still very large, especially for OCO-2 retrieval, resulting the worse performance of OCO-2 retrieval, which also suggest that the bias-correction scheme implemented may need to be improved.

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 baseline, 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 poor-man 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 the simulated CO_2 concentrations with GOSAT posterior fluxes are much closer to the observations than those with OCO-2 estimates. Compared with poor-man 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 only displays slight improvement over poor-man inversion. Generally, the posterior biases from GOSAT 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 GOSAT and OCO-2 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 obvious. 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. It also should be noted that though the OCO-2 XCO_2 retrievals of version b7.3 used in this study perform worse than GOSAT data and in situ measurements in our inversions, one recent study has shown that the newer version of OCO-2 data has a much better performance in constraining carbon flux (Chevallier et al., 2019). With constantly improved retrieval algorithm and bias-correction scheme, more robust estimate of carbon flux from satellite XCO_2 retrievals could be achieved.

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.

Acknowledgements

This work is supported by the National Key R&D Program of China (Grant No: 2016YFA0600204), National Natural Science Foundation of China (Grant No: 41571452), and the Fundamental Research Funds for the Central Universities (Grant No: 090414380021). CarbonTracker CT2016 results provided by NOAA ESRL, Boulder, Colorado, USA from the website at http://carbontracker.noaa.gov.

References

Andres, R. J., Gregg, J. S., Losey, L., Marland, G. and Boden, T. A.: Monthly, global emissions of carbon dioxide from fossil fuel consumption. Tellus B, 63(3), 309–327, https://doi.org/10.1111/j.1600-0889.2011.00530.x, 2011.

Baker, D. F., Bösch, H., Doney, S. C., O’Brien, D., and Schimel, D. S.: Carbon source/sink information provided by column CO_2 measurements from the Orbiting Carbon Observatory, Atmos. Chem. Phys., 10, 4145–4165, https://doi.org/10.5194/acp-10- 4145-2010, 2010.

Basu, S., Guerlet, S., Butz, A., Houweling, S., Hasekamp, O., Aben, I., Krummel, P., Steele, P., Langenfelds, R., Torn, M., Biraud, S., Stephens, B., Andrews, A., and Worthy, D.: Global CO_2 fluxes estimated from GOSAT retrievals of total column CO_2, At- mos. Chem. Phys., 13, 8695–8717, https://doi.org/10.5194/acp- 13-8695-2013, 2013.

Basu, S., Krol, M., Butz, A., Clerbaux, C., Sawa, Y., Machida, T., Matsueda, H., Frankenberg, C., Hasekamp, O. P., and Aben, I.: The seasonal variation of the CO_2 flux over Tropical Asia estimated from GOSAT, CONTRAIL, and IASI, Geophys. Res. Lett., 41, 1809–1815, https://doi.org/10.1002/2013GL059105, 2014.

Blumenstock, T., Hase, F., Schneider, M., García, O.E., and Sepúlveda, E.: TCCON data from Izana, Tenerife, Spain, Release GGG2014R1. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, Pasadena, CA, U.S.A. https://doi.org/10.14291/tccon.ggg2014.izana01.R1, 2017.

Byrd, R. H., Nocedal, J. and Schnabel, R. B.: Representations of Quasi-Newton Matrices and their use in Limited Memory Methods. Math Program. 63(4), 129–156. https://doi.org/10.1007/BF01582063, 1994.

CarbonTracker Team; (2017): Simulated observations of atmospheric carbon dioxide from CarbonTracker release CT2016 (obspack_co2_1_CARBONTRACKER_CT2016_2017-02-06); NOAA Earth System Research Laboratory, Global Monitoring Division. http://dx.doi.org/10.15138/G3G599"

Chatterjee, A., Gierach, M. M., Sutton, A. J., Feely, R. A., Crisp, D., Eldering, A., Gunson, M. R., O'Dell, C. W., Stephens, B. B., and Schimel, D. S.: Influence of El Niño on atmospheric CO_2 over the tropical Pacific Ocean: Findings from NASA's OCO-2 mission, Science, 358, eaam5776, https://doi.org/10.1126/science.aam5776, 2017.

Chevallier, F., Breon, F.-M., and Rayner, P. J.: Contribution of the Orbiting Carbon Observatory to the estimation of CO_2 sources and sinks: Theoretical study in a variational data assimilation framework, J. Geophys. Res.-Atmos., 112, d09307, https://doi.org/10.1029/2006JD007375, 2007.

Chevallier, F., R. J. Engelen, C. Carouge, T. J. Conway, P. Peylin, C. Pickett-Heaps, M. Ramonet, P. J. Rayner, and I. Xueref-Remy (2009), AIRS-based versus flask-based estimation of carbon surface fluxes, J. Geophys. Res., 114, D20303, doi:10.1029/2009JD012311.

Chevallier, F., Ciais P., Conway T.J., Aalto T., Anderson B.E., Bousquet P., Brunke E.G., Ciattaglia L., Esaki Y., Fröhlich M., Gomez A., Gomez-Pelaez A.J., Haszpra L., Krummel P.B., Langenfelds R.L., Leuenberger M., Machida T., Maignan F., Matsueda H., Morguí J.A., Mukai H., Nakazawa T., Peylin P., Ramonet M., Rivier L., Sawa Y., Schmidt M., Steele L.P., Vay S.A., Vermeulen A.T., Wofsy S., and Worthy D.: CO_2 surface fluxes at grid point scale estimated from a global 21 year reanalysis of atmospheric measurements, J. Geophys. Res., 115, D21307, 2010.

Chevallier, F., Palmer, P. I., Feng, L., Boesch, H., O'Dell, C. W., and Bousquet, P.: Toward robust and consistent regional CO_2 flux estimates from in situ and spaceborne measurements of atmospheric CO_2, Geophys. Res. Lett., 41, 1065–1070, https://doi.org/10.1002/2013GL058772, 2014.

Chevallier, F., Remaud, M., O'Dell, C. W., Baker, D., Peylin, P., and Cozic, A.: Objective evaluation of surface- and satellite-driven CO_2 atmospheric inversions, Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2019-213, in review, 2019.

Conway, T. J., Tans, P. P., Waterman, L. S., Thoning, K. W., Kitzis, D. R., Masarie, K. A., and Zhang, N.: Evidence for interannual variability of the carbon cycle from the National Oceanic and Atmospheric Administration/Climate Monitoring and Diagnostics Laboratory Global Air Sampling Network, J. Geophys. Res., 99, 22831–22855, https://doi.org/10.1029/94JD01951, 1994.

Crisp, D., Pollock, H. R., Rosenberg, R., Chapsky, L., Lee, R. A. M., Oyafuso, F. A., Frankenberg, C., O'Dell, C. W., Bruegge, C. J., Doran, G. B., Eldering, A., Fisher, B. M., Fu, D., Gunson, M. R., Mandrake, L., Osterman, G. B., Schwandner, F. M., Sun, K., Taylor, T. E., Wennberg, P. O., and Wunch, D.: The on-orbit performance of the Orbiting Carbon Observatory-2 (OCO-2) instrument and its radiometrically calibrated products, Atmos. Meas. Tech., 10, 59–81, https://doi.org/10.5194/amt-10-59-2017, 2017.

Deng, F. and Chen, J. M.: Recent global CO_2 flux inferred from atmospheric CO_2 observations and its regional analyses, Biogeo- sciences, 8, 3263–3281, https://doi.org/10.5194/bg-8-3263-2011, 2011.

Deng, F., Jones, D. B. A., Henze, D. K., Bousserez, N., Bowman, K. W., Fisher, J. B., Nassar, R., O'Dell, C., Wunch, D., Wennberg, P. O., Kort, E. A., Wofsy, S. C., Blumenstock, T., Deutscher, N. M., Griffith, D. W. T., Hase, F., Heikkinen, P., Sherlock, V., Strong, K., Sussmann, R., and Warneke, T.: Inferring regional sources and sinks of atmospheric CO_2 from GOSAT XCO_2 data, Atmos. Chem. Phys., 14, 3703-3727, https://doi.org/10.5194/acp-14-3703-2014, 2014.

Deng, F., Jones, D. B. A., O'Dell, C. W., Nassar, R., and Parazoo, N. C.: Combining GOSAT XCO_2 observations over land and ocean to improve regional CO_2 flux estimates, J. Geophys. Res. Atmos., 121, 1896–1913, https://doi.org/10.1002/2015JD024157, 2016.

Deutscher, N., Notholt, J., Messerschmidt, J., Weinzierl, C., Warneke, T., Petri, C., Grupe, P., and Katrynski, K.: TCCON data from Bialystok, Poland, Release GGG2014R1. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, Pasadena, CA, U.S.A. http://doi.org/10.14291/tccon.ggg2014.bialystok01.R1/1183984, 2017.

Eldering, A., Boland, S., Solish, B., Crisp, D., Kahn, P., and Gunson, M.: High precision atmospheric CO_2 measurements from space: The design and implementation of OCO-2, in: 2012 IEEE Aerospace Conference, 1–10, https://doi.org/10.1109/AERO.2012.6187176, 2012.

Eldering, A., O'Dell, C. W., Wennberg, P. O., Crisp, D., Gunson, M. R., Viatte, C., Avis, C., Braverman, A., Castano, R., Chang, A., Chapsky, L., Cheng, C., Connor, B., Dang, L., Doran, G., Fisher, B., Frankenberg, C., Fu, D., Granat, R., Hobbs, J., Lee, R. A. M., Mandrake, L., McDuffie, J., Miller, C. E., Myers, V., Natraj, V., O'Brien, D., Osterman, G. B., Oyafuso, F., Payne, V. H., Pol- lock, H. R., Polonsky, I., Roehl, C. M., Rosenberg, R., Schwand- ner, F., Smyth, M., Tang, V., Taylor, T. E., To, C., Wunch, D., and Yoshimizu, J.: The Orbiting Carbon Observatory-2: first 18 months of science data products, Atmos. Meas. Tech., 10, 549–563, https://doi.org/10.5194/amt-10-549-2017, 2017a.

Eldering, A., Wennberg, P. O., Crisp, D., Schimel, D. S., Gun- son, M. R., Chatterjee, A., Liu, J., Schwandner, F. M., Sun, Y., O'Dell, C. W., Frankenberg, C., Taylor, T., Fisher, B., Oster- man, G. B., Wunch, D., Hakkarainen, J., Tamminen, J., and Weir, B.: The Orbiting Carbon Observatory-2 early science investigations of regional carbon dioxide fluxes, Science, 358, eaam5745, https://doi.org/10.1126/science.aam5745, 2017b.

Feng, L., Palmer, P. I., Parker, R. J., Deutscher, N. M., Feist, D. G., Kivi, R., Morino, I., and Sussmann, R.: Estimates of European uptake of CO_2 inferred from GOSAT XCO_2 retrievals: Sensitivity to measurement bias inside and outside Europe. Atmos. Chem. Phys., 16, 1289–1302, https://doi.org/10.5194/acp-16-1289-2016, 2016.

Giglio, L., Randerson, J. T., and van der Werf, G. R.: Analysis of daily, monthly, and annual burned area using the fourth-generation global fire emissions database (GFED4) J. Geophys. Res. Biogeosci., 118, 317–328, https://doi.org/10.1002/jgrg.20042, 2013.

Griffith, D. W. T., Deutscher, N., Velazco, V. A., Wennberg, P. O., Yavin, Y., Keppel Aleks, G., Washenfelder, R., Toon, G. C., Blavier, J.-F., Murphy, C., Jones, N., Kettlewell, G., Connor, B., Macatangay, R., Roehl, C., Ryczek, M., Glowacki, J., Culgan, T., and Bryant, G.: TCCON data from Darwin, Australia, Release GGG2014R0. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, Pasadena, CA, U.S.A. http://doi.org/10.14291/tccon.ggg2014.darwin01.R0/1149290, 2017a.

Griffith, D. W. T., Velazco, V. A., Deutscher, N., Murphy, C., Jones, N., Wilson, S., Macatangay, R., Kettlewell, G., Buchholz, R. R., and Riggenbach, M.: TCCON data from Wollongong, Australia, Release GGG2014R0. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, Pasadena, CA, U.S.A. https://doi.org/10.14291/tccon.ggg2014.wollongong01.R0/1149291, 2017b.

Gurney, K. R., Law, R. M., Denning, A. S., Rayner, P. J., Baker, D., Bousquet, P., Bruhwiler, L., Chen, Y.-H., Ciais, P., Fan, S., Fung, I. Y., Gloor, M., Heimann, M., Higuchi, K., John, J., Maki, T., Maksyutov, S., Masarie, K., Peylin, P., Prather, M., Pak, B. C., Randerson, J., Sarmiento, J., Taguchi, S., Takahashi, T., and Yuen, C.-W.: Towards robust regional estimates of CO_2 sources and sinks using atmospheric transport models, Nature, 415, 626–630, 2002.

Henze, D. K., Hakami, A. and Seinfeld, J. H.: Development of the adjoint of GEOS-Chem, Atmos. Chem. Phys., 7, 2413-2433, 2007.

Heymann, J., Reuter, M., Buchwitz, M., Schneising, O., Bovens- mann, H., Burrows, J. P., Massart, S., Kaiser, J. W., and Crisp, D.: CO_2 emission of Indonesian fires in 2015 estimated from satellite-derived atmospheric CO_2 concentrations, Geophys. Res. Lett., 44, 1537–1544, https://doi.org/10.1002/2016GL072042, 2017.

Houweling, S., Breon, F.-M., Aben, I., R¨odenbeck, C., Gloor, M., Heimann, M., and Ciais, P.: Inverse modeling of CO_2 sources and sinks using satellite data: a synthetic inter-comparison of measurement techniques and their performance as a function of space and time, Atmos. Chem. Phys., 4, 523–538, https://doi.org/10.5194/acp-4-523-2004, 2004.

Houweling, S., Aben, I., Breon, F.-M., Chevallier, F., Deutscher, N., Engelen, R., Gerbig, C., Griffith, D., Hungershoefer, K., Macatangay, R., Marshall, J., Notholt, J., Peters, W., and Serrar, S.: The importance of transport model uncertainties for the estimation of CO_2 sources and sinks using satellite measurements, Atmos. Chem. Phys., 10, 9981–9992, https://doi.org/10.5194/acp-10-9981-2010, 2010.

Houweling, S., Baker, D., Basu, S., Boesch, H., Butz, A., Cheval- lier, F., Deng, F., Dlugokencky, E. J., Feng, L., Ganshin, A., Hasekamp, O., Jones, D., Maksyutov, S., Marshall, J., Oda, T., O'Dell, C. W., Oshchepkov, S., Palmer, P. I., Peylin, P., Poussi, Z., Reum, F., Takagi, H., Yoshida, Y., and Zhuravlev, R.: An intercomparison of inverse models for estimating sources and sinks of CO_2 using GOSAT measurements, J. Geophys. Res.-Atmos., 120, 5253–5266, https://doi.org/10.1002/2014JD022962, 2015.

Hungershoefer, K., Breon, F.-M., Peylin, P., Chevallier, F., Rayner, P., Klonecki, A., Houweling, S., and Marshall, J.: Evaluation of various observing systems for the global monitoring of CO_2 surface fluxes, Atmos. Chem. Phys., 10, 10503–10520, https://doi.org/10.5194/acp-10-10503-2010, 2010.

Jiang, Z., Jones, D. B. A., Kopacz, M., Liu, J., Henze, D. K., and Heald, C.: Quantifying the impact of model errors on top-down estimates of carbon monoxide emissions using satellite observations, J. Geophys. Res., 116, D15306, https://doi.org/10.1029/2010JD015282, 2011.

Kivi, R., Heikkinen, P., and Kyro, E.: TCCON data from Sodankyla, Finland, Release GGG2014R0. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, Pasadena, CA, U.S.A. https://doi.org/10.14291/tccon.ggg2014.sodankyla01.R0/1149280, 2017.

Kopacz, M., Jacob, D. J., Henze, D. K., Heald, C. L., Streets, D. G., and Zhang, Q.: A comparison of analytical and adjoint Bayesian inversion methods for constraining Asian sources of CO using satellite (MOPITT) measurements of CO columns, J. Geophys. Res., 114, D04305, https://doi.org/10.1029/2007JD009264, 2009.

Kopacz, M., Jacob, D. J., Fisher, J. A., Logan, J. A., Zhang, L., Megretskaia, I. A, Yantosca, R. M., Singh, K., Henze, D. K., Burrows, J. P., Buchwitz, M., Khlystova, I., McMillan, W. W., Gille, J. C., Edwards, D. P., Eldering, A., Thouret, V., and Nedelec, P.: Global estimates of CO sources with high resolution by adjoint inversion of multiple satellite datasets (MOPITT, AIRS, SCIAMACHY, TES), Atoms. Chem. Phys., 10, 855-876, 2010.

Kuze, A., Suto, H., Nakajima, M., and Hamazaki, T.: Thermal and near infrared sensor for carbon observation Fourier-transform spectrometer on the Greenhouse Gases Observing Satellite for greenhouse gases monitoring. Appl. Opt., 48, 6716, https://doi.org/10.1364 /AO.48.006716, 2009.

Liu, J., Bowman, K. W., Lee, M., Henze, D. K., Bousserez, N., Brix, H., Collatz, G. J., Menemenlis, D., Ott, L., Pawson, S., Jones, D., and Nassar, R.: Carbon monitoring system flux estimation and attribution: impact of ACOS-GOSAT XCO_2 sampling on the inference of terrestrial biospheric sources and sinks, Tellus B, 66, 22486, https://doi.org/10.3402/tellusb.v66.22486, 2014.

Liu, J., Bowman, K. W., Schimel, D. S., Parazoo, N. C., Jiang, Z., Lee, M., Bloom, A. A., Wunch, D., Frankenberg, C., Sun, Y., O'Dell, C. W., Gurney, K. R., Menemenlis, D., Gierach, M., Crisp, D., and Eldering, A.: Contrasting carbon cycle responses of the tropical continents to the 2015–2016 El Niño, Science, 358, eaam5690, https://doi.org/10.1126/science.aam5690, 2017.

Maksyutov, S., Takagi, H., Valsala, V. K., Saito, M., Oda, T., Saeki, T., Belikov, D. A., Saito, R., Ito, A., Yoshida, Y., Morino, I., Uchino, O., Andres, R. J., and Yokota, T.: Regional CO_2 flux estimates for 2009–2010 based on GOSAT and ground- based CO_2 observations, Atmos. Chem. Phys., 13, 9351–9373, https://doi.org/10.5194/acp-13-9351-2013, 2013.

Messerschmidt, J., Geibel, M. C., Blumenstock, T., Chen, H., Deutscher, N. M., Engel, A., Feist, D. G., Gerbig, C., Gisi, M., Hase, F., Katrynski, K., Kolle, O., Lavrič, J. V., Notholt, J., Palm, M., Ramonet, M., Rettinger, M., Schmidt, M., Sussmann, R., Toon, G. C., Truong, F., Warneke, T., Wennberg, P. O., Wunch, D., and Xueref-Remy, I.: Calibration of TCCON column-averaged CO_2: the first aircraft campaign over European TCCON sites, Atmos. Chem. Phys., 11, 10765-10777, https://doi.org/10.5194/acp-11-10765-2011, 2011.

Miller, C. E., Crisp, D., DeCola, P. L., Olsen, S. C., Randerson, J. T., Michalak, A. M., Alkhaled, A., Rayner, P., Jacob, D. J., Suntharalingam, P., Jones, D. B. A., Denning, A. S., Nicholls, M. E., Doney, S. C., Pawson, S., Boesch, H., Connor, B. J., Fung, I. Y., O'Brien, D., Salawitch, R. J., Sander, S. P., Sen, B., Tans, P., Toon, G. C.,Wennberg, P. O.,Wofsy, S. C., Yung, Y. L., and Law, R. M.: Precision requirements for space-based XCO_2 data, J. Geophys. Res., 112, D10314, https://doi.org/10.1029/2006JD007659, 2007.

Miller, S. M., Michalak, A. M., Yadav, V., and Tadić, J. M.: Characterizing biospheric carbon balance using

CO_2 observations from the OCO-2 satellite, Atmos. Chem. Phys., 18, 6785-6799, https://doi.org/10.5194/acp-18-6785-2018, 2018.

Morino, I., Matsuzaki, T., and Shishime, A.: TCCON data from Tsukuba, Ibaraki, Japan, 125HR, Release GGG2014R2. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, Pasadena, CA, U.S.A. http://doi.org/10.14291/tccon.ggg2014.tsukuba02.R2, 2017.

Nassar, R., Jones, D. B. A., Suntharalingam, P., Chen, J. M., Andres, R. J., Wecht, K. J., Yantosca, R. M., Kulawik, S. S., Bowman, K. W., Worden, J. R., Machida, T., and Matsueda, H.: Modeling global atmospheric CO_2 with improved emission inventories and CO_2 production from the oxidation of other carbon species, Geosci. Model Dev., 3, 689–716, https://doi.org/10.5194/gmd-3-689-2010, 2010.

Nassar, R., Hill, T. G., McLinden, C. A., Wunch, D., Jones, D. B. A., and Crisp, D.: Quantifying CO_2 emissions From Individual Power Plants from Space, Geophys. Res. Lett., 44, 10045– 10053, https://doi.org/10.1002/2017GL074702, 2017.

Notholt, J., Petri, C., Warneke, T., Deutscher, N., Buschmann, M., Weinzierl, C., Macatangay, R., and Grupe, P.: TCCON data from Bremen, Germany, Release GGG2014R0. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, Pasadena, CA, U.S.A. https://doi.org/10.14291/tccon.ggg2014.bremen01.R0/1149275, 2017a.

Notholt, J., Schrems, O., Warneke, T., Deutscher, N., Weinzierl, C., Palm, M., Buschmann, M., and AWI-PEV Station Engineers: TCCON data from Ny Alesund, Spitzbergen, Norway, Release GGG2014R0. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, Pasadena, CA, U.S.A. https://doi.org/10.14291/tccon.ggg2014.nyalesund01.R0/1149278, 2017b.

ObsPack: Cooperative Global Atmospheric Data Integration Project, Multi-laboratory compilation of atmospheric carbon dioxide data for the period 1957–2015, obspack_co2_1_GLOBALVIEWplus_v2.1_2016-09-02, NOAA Earth System Research Laboratory, Global Monitoring Division, https://doi.org/10.15138/G3059Z, 2016.

O'Dell, C., Connor, B., Bösch, H., O’Brien, D., Frankenberg, C., Castano, R., Christi, M., Eldering, D., Fisher, B., Gunson, M., McDuffie, J., Miller, C. E., Natraj, V., Oyafuso, F., Polonsky, I., Smyth, M., Taylor, T., Toon, G., Wennberg, P., and Wunch, D.: The ACOS CO_2 retrieval algorithm – Part 1: Description and validation against synthetic observations, Atmos. Meas. Tech., 5, 99-121, https://doi.org/10.5194/amt-5-99-2012, 2012.

Oda, T. and Maksyutov, S. 2011. A very high-resolution (1 km x 1 km) global fossil fuel CO_2 emission inventory derived using a point source database and satellite observations of nighttime lights. *Atmos. Chem. Phys.* 11, 543 ‑ 556.

Park, B. C. and Prather, M. J.: CO_2 source inversions using satellite observations of the upper troposphere, Geophys. Res. Lett., 28, 4571–4574, https://doi.org/10.1029/2001GL013604, 2001.

Parrington, M., Palmer, P. I., Henze, D. K., Tarasick, D. W., Hyer, E. J., Owen, R. C., Clerbaux, C., Bowman, K. W., Deeter, M. N., Barratt, E. M., Coheur, P.-F., Hurtmans, D., George, M., and Worden, J. R.: The influence of boreal biomass burning emissions on the distribution of tropospheric ozone over North America and the North Atlantic during 2010, Atmos. Chem. Phys., 12, 2077-2098, 2012.

Patra, P. K., Crisp, D., Kaiser, J. W., Wunch, D., Saeki, T., Ichii, K., Sekiya, T., Wennberg, P. O., Feist, D. G., Pollard, D. F., Griffith, D. W. T., Velazco, V. A., De Maziere, M., Sha, M. K., Roehl, C., Chatterjee, A., and Ishijima, K.: The Orbiting Carbon Observa- tory (OCO-2) tracks 2–3 peta-gram increase in carbon release to the atmosphere during the 2014–2016 El Niño, Sci. Rep.-UK, 7, 13567, https://doi.org/10.1038/s41598-017-13459-0, 2017.

Peters, W., Jacobson, A. R., Sweeney, C., Andrews, A. E., Conway, T. J., Masarie, K., Miller, J. B., Bruhwiler, L. M. P., P´etron, G., Hirsch, A. I.,Worthy, D. E. J.,Werf, G. R. V. D., Randerson, J. T., Wennberg, P. O., Krol, M. C., and Tans, P. P.: An atmospheric perspective on North American carbon dioxide exchange: CarbonTracker, P. Natl. Acad. Sci., 104, 18925–18930, 2007..

Peylin, P., Law, R. M., Gurney, K. R., Chevallier, F., Jacobson, A. R., Maki, T., Niwa, Y., Patra, P. K., Peters, W., Rayner, P. J., Rödenbeck, C., van der Laan-Luijkx, I. T., and Zhang, X.: Global atmospheric carbon budget: results from an ensemble of atmospheric CO_2 inversions, Biogeosciences, 10, 6699–6720, https://doi.org/10.5194/bg-10-6699-2013, 2013.

Potter, C. S., Randerson, J. T., Field, C. B., Matson, P. A., Vitousek, P. M., Mooney, H. A., and Klooster, S. A.: Terrestrial ecosystem production: A process model based on global satellite and surface data, Global Biogeochem. Cycles, 7(4), 811–841, https://doi.org/10.1029/93GB02725, 1993.

Rayner, P. J. and O'Brien, D. M.: The utility of remotely sensed CO_2 concentration data in surface source inversions, Geophys. Res. Lett., 28, 175–178, https://doi.org/10.1029/2000GL011912, 2001.

Reuter, M., Buchwitz, M., Hilker, M., Heymann, J., Schneising, O., Pillai, D., Bovensmann, H., Burrows, J. P., Bösch, H., Parker, R., Butz, A., Hasekamp, O., O'Dell, C. W., Yoshida, Y., Gerbig, C., Nehrkorn, T., Deutscher, N. M., Warneke, T., Notholt, J., Hase, F., Kivi, R., Sussmann, R., Machida, T., Matsueda, H., and Sawa, Y.: Satellite-inferred European carbon sink larger than expected, Atmos. Chem. Phys., 14, 13739-13753, https://doi.org/10.5194/acp-14-13739-2014, 2014.

Reuter, M., Buchwitz, M., Hilker, M., Heymann, J., Bovensmann, H., Burrows, J. P., Houweling, S., Liu, Y. Y., Nassar, R., Chevallier, F., Ciais, P., Marshall, J., and Reichstein, M.: How Much CO_2 Is Taken Up by the European Terrestrial Biosphere?. Bull. Amer. Meteor. Soc., 98, 665–671, https://doi.org/10.1175/BAMS-D-15-00310.1, 2017.

Rienecker, M. M., Suarez, M. J., Todling, R., Bacmeister, J., Takacs, L. and co-authors: The GEOS-5 Data Assimilation System-Documentation of versions 5.0.1 and 5.1.0, and 5.2.0 NASA Tech. Rep. Series on Global Modeling and Data Assimilation, NASA/TM-2008-104606, Vol. 27, 92 pp, 2008.

Rodgers, C. D.: Inverse Methods for Atmospheric Sounding: Theory and Practice, World Scientific Publishing Co Inc, Singapore, chapter 2, 2000.

Saeki, T., Maksyutov, S., Saito, M., Valsala, V., Oda, T., An- dres, R. J., Belikov, D., Tans, P., Dlugokencky, E., Yoshida, Y., Morino, I., Uchino, O., and Yokota, T.: Inverse modeling of CO_2 fluxes using GOSAT data and multi-year ground-based obser- vations, SOLA, 9, 45–50, https://doi.org/10.2151/sola.2013-011, 2013.

Sherlock, V., Connor, B., Robinson, J., Shiona, H., Smale, D., and Pollard, D.: TCCON data from Lauder, New Zealand, 125HR, Release GGG2014R0. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, Pasadena, CA, U.S.A. https://doi.org/10.14291/tccon.ggg2014.lauder02.R0/1149298, 2017.

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.

Suntharalingam, P., Jacob, D. J., Palmer, P. I., Logan, J. A., Yantosca, R. M. and co-authors: Improved quantification of Chinese carbon fluxes using CO_2/CO correlations in Asian outflow. J. Geophys. Res. 109, D18S18, https://doi.org/10.1029/2003JD004362, 2004.

Sussmann, R., and Rettinger, M.: TCCON data from Garmisch, Germany, Release GGG2014R2. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, Pasadena, CA, U.S.A. https://doi.org/10.14291/tccon.ggg2014.garmisch01.R2, 2017.

Tarantola, A.: Inverse Problem Theory and Methods for Model Parameter Estimation, Soc. Industr. App.l Math., Philadelphia, PA, USA, 2004.

van der Werf, G. R., Randerson, J. T., Giglio, L., Collatz, G. J., Mu, M., Kasibhatla, P. S., Morton, D. C., DeFries, R. S., Jin, Y., and van Leeuwen, T. T.: Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009), Atmos. Chem. Phys., 10, 11707–11735, https://doi.org/10.5194/acp-10-11707-2010, 2010.

Wang, X., Guo, Z., Huang, Y. P., Fan, H. J., and Li, W. B.: A cloud detection scheme for the Chinese carbon dioxide observation satellite (TANSAT). Adv. Atmos. Sci., 34(1), 16–25, https://doi.org/10.1007/s00376-016-6033-y, 2017.

Warneke, T., Messerschmidt, J., Notholt, J., Weinzierl, C., Deutscher, N., Petri, C., Grupe, P., Vuillemin, C., Truong, F., Schmidt, M., Ramonet, M., and Parmentier, E.: TCCON data from Orleans, France, Release GGG2014R0. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, Pasadena, CA, U.S.A. https://doi.org/10.14291/tccon.ggg2014.orleans01.R0/1149276, 2017.

Wennberg, P. O., Roehl, C., Wunch, D., Toon, G. C., Blavier, J.-F., Washenfelder, R., Keppel-Aleks, G., Allen, N., and Ayers, J.: TCCON data from Park Falls, Wisconsin, USA, Release GGG2014R1. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, Pasadena, CA, U.S.A. http://doi.org/10.14291/tccon.ggg2014.parkfalls01.R1, 2017.

Wennberg, P. O., Wunch, D., Roehl, C., Blavier, J.-F., Toon, G. C., Allen, N., Dowell, P., Teske, K., Martin, C., and Martin, J.: TCCON data from Lamont, Oklahoma, USA, Release GGG2014R1. TCCON data archive, hosted by CaltechDATA, California Institute of Technology, Pasadena, CA, U.S.A. https://doi.org/10.14291/tccon.ggg2014.lamont01.R1/1255070, 2017. Wilkerson, J. T., Jacobson, M. Z., Malwitz, A., Balasubramanian, S., Wayson, R., Fleming, G., Naiman, A. D., and Lele, S. K.: Analysis of emission data from global commercial aviation: 2004 and 2006, Atmos. Chem. Phys., 10, 6391-6408, https://doi.org/10.5194/acp-10-6391-2010, 2010.

Wunch, D., Toon, G. C., Wennberg, P. O., Wofsy, S. C., Stephens, B. B., Fischer, M. L., Uchino, O., Abshire, J. B., Bernath, P., Biraud, S. C., Blavier, J.-F. L., Boone, C., Bowman, K. P., Browell, E. V., Campos, T., Connor, B. J., Daube, B. C., Deutscher, N. M., Diao, M., Elkins, J. W., Gerbig, C., Gottlieb, E., Griffith, D. W. T., Hurst, D. F., Jimenez, R., Keppel-Aleks, G., Kort, E. A., Macatangay, R., Machida, T., Matsueda, H., Moore, F., Morino, I., Park, S., Robinson, J., Roehl, C. M., Sawa, Y., Sherlock, V., Sweeney, C., Tanaka, T., and Zondlo, M. A.: Calibration of the Total Carbon Column Observing Network using aircraft profile data, Atmos. Meas. Tech., 3, 1351-1362, doi:10.5194/amt-3-1351-2010, 2010.

Wunch, D., Wennberg, P. O., Toon, G. C., Connor, B. J., Fisher, B., Osterman, G. B., Frankenberg, C., Mandrake, L., O'Dell, C., Ahonen, P., Biraud, S. C., Castano, R., Cressie, N., Crisp, D., Deutscher, N. M., Eldering, A., Fisher, M. L., Griffith, D. W. T., Gunson, M., Heikkinen, P., Keppel-Aleks, G., Kyrö, E., Lindenmaier, R., Macatangay, R., Mendonca, J., Messer- schmidt, J., Miller, C. E., Morino, I., Notholt, J., Oyafuso, F. A., Rettinger, M., Robinson, J., Roehl, C. M., Salawitch, R. J., Sherlock, V., Strong, K., Sussmann, R., Tanaka, T., Thomp- son, D. R., Uchino, O., Warneke, T., and Wofsy, S. C.: A method for evaluating bias in global measurements of CO_2 total columns from space, Atmos. Chem. Phys., 11, 12317–12337, https://doi.org/10.5194/acp-11-12317-2011, 2011.

Wunch, D., Wennberg, P. O., Osterman, G., Fisher, B., Naylor, B., Roehl, C. M., O'Dell, C., Mandrake, L., Viatte, C., Kiel, M., Griffith, D. W. T., Deutscher, N. M., Velazco, V. A., Notholt, J., Warneke, T., Petri, C., De Maziere, M., Sha, M. K., Sussmann, R., Rettinger, M., Pollard, D., Robinson, J., Morino, I., Uchino, O., Hase, F., Blumenstock, T., Feist, D. G., Arnold, S. G., Strong, K., Mendonca, J., Kivi, R., Heikkinen, P., Iraci, L., Podolske, J., Hillyard, P. W., Kawakami, S., Dubey, M. K., Parker, H. A., Sepulveda, E., García, O. E., Te, Y., Jeseck, P., Gunson, M. R., Crisp, D., and Eldering, A.: Comparisons of the Orbiting Carbon Observatory-2 (OCO-2) XCO_2 measurements with TCCON, At- mos. Meas. Tech., 10, 2209–2238, https://doi.org/10.5194/amt- 10-2209-2017, 2017.

Yang, D. X., Liu, Y., Cai, Z. N., Chen, X., Yao, L., and Lu, D. R.: First global carbon dioxide maps produced from TanSat measurements. Adv. Atmos. Sci., 35(6), 621–623, https://doi.org/10.1007/s00376-018-7312-6, 2018.

Zhu, C., Byrd, R. H., Lu, P. and Nocedal, J.: L-BFGS-B: algorithm 778: L-BFGS-B, FORTRAN routines for large scale bound constrained optimization. ACM Trans. Math. Softw. 23(4), 550_560. https://doi.org/10.1145/279232.279236, 1997.