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Interactive comment on "A dual-pass carbon cycle data assimilation system to estimate surface CO_2 fluxes and 3D atmospheric CO_2 concentrations from spaceborne measurements of atmospheric CO_2" *by* Rui Han and Xiangjun Tian

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Responses to Anonymous Referee #2

We would like to thank the reviewer for carefully reading our paper and for all the valuable questions/comments/suggestions. We have thoroughly studied the reports and made a substantial revision to our paper by incorporating all suggestions given in the reports. Below we give our itemized responses.

Comment:

“Since the chief problem with these forward-running assimilation schemes in the past has been the shortness of the assimilation window, which truncates the span across which the dynamical constraint between fluxes and concentrations provided by the atmospheric transport model can operate, it is not clear what benefit is gained by both shortening this assimilation window and removing the flux constraint in the first step of the assimilation. The explanation given in the text for this ("to reduce the influence of the background flux on the initial CO2 concentration") does not make sense to this reviewer: it would seem more logical to use a longer assimilation window, so that the background fluxes (those before the start of the assimilation window) play less of a role, being further back in time with respect to the measurements being assimilated in the window. Given these issues, I am perplexed that the OSSE results presented show that this newer approach is somehow giving results that are closer to the truth than before – I would have thought that a properly-designed OSSE would show the opposite.”

Response:

The window length of one assimilation system is systematically determined by the forecast model (the Atmospheric Chemistry Transport Model), model resolution, observation, assimilation algorithm and system framework. Therefore, the assimilation window length is usually not fixed in different systems.

Table 1 shows that the Tan-Tracker (v1) is substantially different from the Carbon Tracker (CT) and even its previous version (Tan-Tracker, v0). This is not surprising that they have different window lengths because of the above significant differences in the two assimilation systems. Carful comparisons also show that the Tan-Tracker (v0) is much similar to Carbon Tracker (CT), which leads to their similar window lengths.

However, despite that, we don’t think the window length should be fixed in one single assimilation system. It will likely change as the incoming observations and the resolutions, which usually should be determined through sensitivity experiments (as done in this work).

In addition, it is not a technically difficult task to lengthen the assimilation window in Tan-Tracker (v1). It's precisely because that our sensitivity experiments choose the two weeks as the final OSSEs.

Tan-Tracker (v1) uses dual-pass assimilation strategy to assimilate satellite XCO2 observations which can reduce the impact of localization error caused by sparse observation and accumulated error of historical optimized fluxes. In the current assimilation window, the simulated CO2 concentration errors originated from both the initial CO2 at the beginning of this window and the background flux of this window (see page 4 line 21). More specifically, the initial CO2 contains accumulated error of the historical optimal fluxes also contains error of the start initial CO2 (the first window). These errors entangled with the model evolution, which is indeed difficult to optimize the CO2 concentrations and fluxes altogether. In the dual-pass assimilation strategy, a shorter CO2 assimilation pass (3-day) is first adopted to optimize the initial CO2 concentrations (shorter window can reduce the influence of background flux of this window on initial CO2 assimilation). The optimized initial CO2 concentrations at the beginning of this window are then used for the following flux assimilation pass (14-day), which is a reasonable strategy to differentiate the errors from the initial CO2 and the background fluxes (For more details, please see abstract, section 2.1, section 4 and Fig.1).

Furthermore, to guarantee "mass-balance", we start the update section by the background initial CO2 (instead of the optimized initial CO2 concentrations obtained in the first assimilation pass) forced by optimized fluxes obtained in the second assimilation pass.

Comment:

"Measurement information in this scheme, as in CarbonTracker, can only be propagated backwards to previous times as far as the length of the assimilation window (here, two weeks (or 3 days?), in v0 5-7 weeks, in CarbonTracker 5 weeks, though this has been increased to 3-6 months in the latest annual release). The measurement information can only modify fluxes within this window – any corrective information coming from earlier fluxes is then mis-attributed to fluxes inside this span. This attribution or localization error grows worse as the assimilation window is shortened. In the past when only in situ data (mostly at the surface) was available, this was a significant problem: in many areas of the world, CO2 fluxes would not be "seen" at the measurement sites until many weeks, or even months, had transpired (think fluxes from the tropical land regions, the effect of which would be transported up due to the mainly convective transport there and not be seen until it came down later at higher latitudes or else got lucky enough to be observed by an airplane before then). In this case, the localization of these far-field fluxes to the near-field around the measurements would cause large flux errors. Now, with satellite data this is less of an issue (there is generally an overpass of the satellite within 400 km of any spot on the globe at least once a week), but clouds and high aerosol conditions in the tropics reduce coverage there and suggest an assimilation window of at least several weeks would still be wise; the ability of the satellites to see a signal anywhere in the column both helps see the influence of the surface fluxes but also hurts by making it more difficult to say where the signal came from. And systematic errors (biases) in the satellite data further limit its usefulness. Given this, I would think that the powerful dynamical constraint provided by the transport models should not be cast aside by using assimilation windows as short as is done here. (Yes, the transport models have their own inaccuracies, but one can always use several of them to get an idea of their influence.)"

Response:

The observation coverage, column averaged CO2 observations and systematic errors are problems encountered when using satellite data. Tan-Tracker (v1) mitigates the side effects by using proper window length and observation operator (Please see the above response and section 2.1, section 4 and Fig.1).

OCO-2 can provide a large amount of XCO2 observations with high spatial and temporal resolution. There are about 10ˆ5 observations per day, meaning 10ˆ6∼10ˆ7 observations per flux assimilation window (14-day). After rigorous data quality control and data thinning, about 10ˆ5∼10ˆ6 observations will be assimilated into Tan-Tracker (v1) within one flux assimilation pass (see Fig.2). And the sun-synchronous orbit of OCO-2 has a 16-day (233 orbit) ground track repeat cycle. This means that the appropriate 14-day flux assimilation window has a better global observations coverage with less repeat location (see Fig.2).

Moreover, column averaged observations XCO2 can influence each model level by using observation operator (For more details, please see section 3.1 and Eq.31). In current Tan-Tracker (v1), we mainly focus on assimilating satellite data and adopting proper strategy to find appropriate surface flux inversion; In the future, we will use multi-source CO2 observations (including in-situ observations) and be more accurate in resolving surface flux signal.

Additionally, we did not consider the observation systematic errors in OSSEs (For more details, please see section 3.1), but we have used OCO-2 data with bias correction in real assimilation experiments; And we believe that the XCO2 retrieval team will make continuous efforts to eliminate the systematic bias (OCO-2 Science Team, 2017; O'Dell et al., 2018).

Using the novel dual-pass assimilation strategy and assimilating OCO-2 satellite observations, Tan-Tracker (v1) does not require a long assimilation window. This conclusion can also be drawn from OSSEs of window length (For more details, please see section 3.3.3).

Comment:

"The estimation of the CO2 fields and CO2 fluxes in two steps also seems problematic to me. Estimating the CO2 fields first without the flux constraint seems to allow one to throw out the mass balance imposed by the transport model for the previous fluxes completely. The error caused by this should them project into the second step in which the fluxes are estimated. The two-step process would seem to eliminate the ability to solve for correlations between errors in the fluxes and errors in the initial concentration field.

In my view, the direction taken here towards shorter assimilation windows and a looser constraint from the transport model seems to be misguided. I would be more interested in the OSSEs quantifying the truncation errors incurred from these short windows, rather than what is shown here (I can't understand why the OSSEs give better results and I am suspicious that the OSSE setup does not capture all the relevant errors). I would not be surprised if CO2 flux results obtained with this new v1 TanSat system are similar to those given by the old "mass-balance" methods of 20+ years ago: noisy to the point of making it difficult to identify the actual flux signal beneath the noise."

Response:

The "mass balance" issue of Tan-Tracker (v1) is not clearly explained in the previous version of this manuscript. To state it clear, we modify a confusing use of Ca to Cb in Fig.1, add "background initial CO2" in Page 5 line 7 and add the descriptions in Page 15 line 7.

Mass balance is important for a carbon cycle assimilation system. In Tan-Tracker (v1), CO2 assimilation pass is a directly change to the atmospheric carbon pool and will result in flux bias if accumulated through the whole assimilation process. To avoid this, the update section starts from the background initial CO2; As a result, the analysis CO2 concentrations are forced by the model and optimized fluxes only, starting from background initial CO2 of first window. This also means chemical transport model can impose continuous constraint on flux and CO2 without truncation error. In other words, optimized flux is not only the best-fitting of current window constrained by observations under low initial CO2 error, but the best-fitting of the whole assimilation progress constrained by model and mass balance.

reference

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Please also note the supplement to this comment:
https://www.geosci-model-dev-discuss.net/gmd-2019-54/gmd-2019-54-AC3-supplement.pdf

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Table 1. Differences between Tan-Tracker (v1), Tan-Tracker (v0) and CT

	Tan-Tracker (v1)	**Tan-Tracker (v0)**	**Carbon Tracker (CT)**
Forecast model	GEOS-Chem	GEOS-Chem	TM5
Assimilation algorithm	(the nonlinear least squares) 4DVar (take the forecast model as the strong constraint), to assimilate all the observations simultaneously	POD-4DVar (actually one Kalman smoother, see Tian et al., 2018)	EnSRF (Very similar to Kalman smoother), to assimilate observations one by one
Observations	Satellite XCO2 (about 10^5 observations per day)	In-situ (about 10^3 per week)	In-situ (about 10^3 per week)
Assimilation framework	Dual-pass assimilation framework (3days, 2 weeks)	Joint-data assimilation framework	Observation window + lag window
Localization scheme	Efficient localization scheme proposed by Tian et al. (2018) and Zhang and Tian (2018)	A simple localization scheme (Tian and Feng, 2015)	Through: $\mathbf{P} = \mathbf{P} \cdot \mathbf{L}$ $\mathbf{L} = e^{-d_{ij}/l}$

Fig. 1.

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