

Interactive comment on “Profiling tropospheric CO₂ using the Aura TES and TCCON instruments” by L. Kuai et al.

Anonymous Referee #1

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We would thank referees for their comments. Please see our reply below. Comments are in black and responses are in [blue](#).

This manuscript describes the retrieval of CO₂ using measurements from the TES instrument on the Aura satellite and ground-based remote sensing from TCCON. The combination of TIR and NIR wavelengths provides a ‘profile’ with two pieces of vertical information. The benefit gained by separating the vertical column is the ability to isolate the boundary layer from the free troposphere, since the boundary layer is where surface sources and sinks actually interact with the atmosphere, and thus of greater interest than a column-average.

The topic of this manuscript is appropriate for AMT and the work presents a significant contribution to the field. The quality of the scientific results is good. The overall presentation quality is good, but one weakness was the choice of citations, which were often not appropriate; however this can be improved based on the comments below, and does not impact or reflect on the scientific findings.

The work is original and also long overdue. As stated in the manuscript, the concept of combining NIR and TIR observations to derive vertical information on atmospheric CO₂ was described in Christi and Stephens (2004), but to my knowledge, the present work is the first study to implement the concept using real remote sensing observations. At the close of the introduction the authors state “We do not use the direct profiling approach discussed in Christi and Stephens (2004) because we found that spectroscopic errors and sampling error due to poor co-

location of the NIR and IR data currently result in unphysical retrieved CO2 profiles. Instead we simply subtract free tropospheric column estimates from total column estimates in order to quantify lower tropospheric CO2 column amounts.” I would have liked to see more details and clarification and perhaps an example illustrating why the joint NIR+TIR retrieval did not work, since if there are any factors that will prevent the approach from working with real data, this would be an important finding for future missions planning to apply the concept, or perhaps even upcoming work combining GOSAT NIR+TIR.

Specific Comments and Technical Corrections

- P4496, line 4-5: “model transport errors” should simply be “model transport”

Will be changed. Thank you.

- P4496, line 23: “precisions” should be “precision”

Will be changed. Thank you.

- P4497, line 1: The paper should do a better job of distinguishing between ground based in situ and remote sensing observations.

I agree with the reviewer that we have to clarify the difference between the ground-based in situ and ground-based remote sensing observations. In this paper, TCCON FTS measurements are ‘the ground-based remote sensing observations’ and flight measurements are in situ observations. There are no other ground-based measurements used in this study. We have revised the words in the text accordingly.

- P4497, line 24: The authors fail to mention SCIAMACHY NIR observations here, with the statement “starting with GOSAT”, although they do mention SCIAMACHY observations on page 4510. Also, GOSAT is the satellite name, TANSO-FTS is the instrument name.

Page 4497, L24, we have changed the words as noted below:

“Total column CO2 data are calculated from solar near infrared (NIR) measurements from the Total Carbon Column Observatory Network (TCCON) (Wunch et al., 2010, 2011a), as well as space-borne instruments, starting from SCIAMACHY (Schneising et al., 2011, 2012) and GOSAT (Yoshida et al., 2009;Wunch et al., 2011b;Yoshida et al., 2011;Crisp et al., 2012;O’Dell et al., 2012).”

- P4497, line 24-29: These citations are poorly chosen. Crisp et al. 2004 should not be cited for GOSAT since it is about OCO with no mention of GOSAT. Crisp et al. 2012 AMT would be appropriate. Yoshida et al. 2009 is not listed in the

references, but the authors probably mean Yoshida et al. 2011 AMT, which needs to be added.

The references have been changed.

- Velazco et al. 2011 is a CarbonSat constellation paper, Bovensmann et al. 2010 is the original CarbonSat paper. Yoshida et al. and Yokota et al. 2009 are not appropriate citations for GOSAT-2 since they do not mention the successor mission, but at present I believe only presentations for this upcoming mission are available. The OCO-2 launch is scheduled for July 2014, so “later this decade” is a poor choice of words, since it is less than 2 years away. “The near future” is a poor choice of words for CarbonSat and GOSAT-2. GOSAT-2 will likely launch later this decade, possibly as early as 2017. CarbonSat is still in competition, and if selected will launch no earlier than 2019. However, none of these projected launch dates are firm, since delays for various reasons are inevitable.

We have rephrased the sentences using the reviewer’s information. Page 4497, L26:

‘Similar space-borne instruments include OCO-2 which is expected to be launched in 2014 (Crisp et al., 2004), and GOSAT-2 (Yokota et al., 2009; Yoshida et al., 2011), which are also expected to be launched later this decade. In addition, Carbonsat (Bovensmann et al., 2010; Velazco et al., 2011) is a proposed instrument that could also be launched in the next decade.’

- P4497, line 29 to p4498, line 1: A distinction between ground-based in situ and remote sensing should be made here. It might also be worth mentioning (somewhere) that TCCON ground-based remote sensing facilitates comparisons between in situ measurements and satellites.

We have changed the paragraph to:

‘Ground-based FTS measurements such as TCCON instruments have high precision and accuracy compared to satellite instruments but limited spatial coverage. TCCON measurements are therefore a valuable resource for validation of SCIAMACHY, GOSAT and OCO-2 satellite measurements. In addition to the column CO₂ from NIR measurements, free tropospheric CO₂ measurements can be made from passive thermal infrared satellite instruments such as TES (Kulawik et al., 2010; Kulawik et al., 2012) and AIRS (Chahine et al., 2005). All these measurements by different techniques play important roles in the carbon flux inversion problem and provide complementary information of the atmospheric CO₂ distribution. However, none of these instruments measure the lower tropospheric CO₂.’

- P4498, line 19: TCCON is not an instrument, it is a network of instruments.

We have changed it to:

'These observations are obtained by a Fourier Transform Spectrometer instrument, with a precise solar tracking system, which measures incoming sunlight with high spectral resolution (0.02 cm⁻¹) and high signal to noise ratio (SNR) between 500 and 885, depending on the spectral region observed (Washenfelter et al., 2006).'

- P4498, line 22: "recorded spectral region range" can simply be replaced with "recorded spectra"

Fixed. Thank you.

- P4499, line 13: Surprisingly the authors do not cite their own paper Kuai et al. 2012, "Vertically constrained CO₂ retrievals from TCCON measurements", JQSRT.

We have added this reference.

- P4498, line 23-26: (Beer et al. 2001) should come after "1 TES measurement every 100 km approximately" not after a reference to GEOS-Chem. Similarly Kulawik et al. (2010) should come earlier in the paragraph. I am not sure if Kulawik et al. 2011 (AGU presentation) is really needed or if this should just be replaced with Kulawik et al. 2012 ACPD?

We have rearranged references (Page 4499, L23-26):

'Because the sampling for the TES CO₂ measurements is sparse (e.g., 1 measurement every 100km approximately) and passing over the Lamont TCCON site every 16 days (Beer et al., 2001), we assimilated the CO₂ measurements into the GEOS-Chem model, a global 3-D chemical transport model (CTM) (Nassar et al., 2010; Kulawik et al., 2010, 2012).'

- P4500, line 9: I would have expected there to be a better citation than the Kulawik et al, papers for SGP-ARM data.

We have replaced the reference for SGP-ARM site with 'Biraud et al., 2012'.

'..... at the Southern Great Plains (SGP) ARM site (Biraud et al., 2012)(<http://www.arm.gov/campaigns/aaf2008acme>) over the year 2009.'

- P4502, line 1: Do the authors have a citation for the 1% bias for the O₂ A-Band? Various retrieval algorithms (ACOS, NIES, RemoteC, . . .) are applying different correction factors.

Yes, we have used 'Wunch et al., 2010, 2011a' as citations for 1% bias in TCCON XCO₂ induced from O₂ retrievals. Actually, different from GOSAT retrievals by ACOS, NIES, RemoteC,, it is O₂ 1.27 micron band that is used to retrieve O₂ by TCCON not A-band which is used by GOSAT.

Page 4502, L 1:

'Because O₂ normalized estimates of XCO₂ have higher precision but about 1% negative bias (Wunch et al., 2010;Wunch et al., 2011a) (Fig. 3), we need to remove the mean bias in TCCON XCO₂ when estimating the total column amount.'

- P4502: A brief description of the GEOS-Chem CO₂ modeling setup is needed to clarify the version number, horizontal and vertical grids, standard fluxes or others, and whether the model runs were evaluated using some in situ data.

We have move A5 to section 2.2 and have rewritten this section as below. Page 4499 L18:

'Free tropospheric CO₂ estimates are derived from thermal IR radiances measured by the Aura Tropospheric Emission Spectrometer (TES) (Beer et al., 2001). The TES instrument measures the infrared radiance emitted by Earth's surface and atmospheric gases and particles from space. These measurements have peak sensitivity to the midtropospheric CO₂ at ~ 500 hPa (Kulawik et al., 2012). Because the sampling for the TES CO₂ measurements is sparse (e.g., 1 measurement every 100km approximately) and passing over the Lamont TCCON site every 16 days (Beer et al., 2001), we assimilated the CO₂ measurements into the GEOS-Chem model, a global 3-D chemical transport model (CTM) (Nassar et al., 2010; Kulawik et al., 2010, 2012).

GEOS-Chem (V8.2.1) is a global 3-D chemical transport model (CTM) for atmospheric composition, with sources and additional modifications specific to the carbon cycle as described in (Nassar et al., 2010) and (Kulawik et al., 2011). It has 2°×2.5° resolution and 47 hybrid-sigma vertical levels. Surface fluxes are described in Table 1.

TES at all pressure levels between 40° S and 40° N, along with the predicted sensitivity and errors, was assimilated for the year 2009 using 3d-var assimilation. We compare model output with and without assimilation to surface based in situ aircraft measurements from the US DOE Atmospheric Radiation Measurement (ARM) Southern Great Plains site during the ARM-ACME (Biraud et al., 2012, <http://www.arm.gov/campaigns/aaf2008acme>) and HIPPO-2 (hippo.ucar.edu/) mission (Kulawik et al., 2012). We find improvement in the seasonal cycle amplitude in the mid-troposphere at the SGP site, but also discrepancies with HIPPO at remote

oceanic sites, particularly outside of the latitude range of assimilation (Kulawik et al., 2012).

We use the results from the assimilation as our free-tropospheric estimates of CO₂. The uncertainties in the assimilation fields are calculated by comparison to aircraft data as discussed in Sect. 5.2.'

Table 1. Surface fluxes used in GEOS-Chem model

Biosphere	CASA-GFED3-v2 (3hr) (cmsflux.jpl.nasa.gov)
Biomass burning	GFED3-Fire-v2 (daily) (cmsflux.jpl.nasa.gov)
Bio fuel	GFED3-fuel-v2 (monthly) (cmsflux.jpl.nasa.gov)
Fossil fuel	CDIAC (monthly) (Nassar et al. 2010)
Ocean	ECCO2-Darwin (daily) (cmsflux.jpl.nasa.gov) (Brix et al., in prep.)
Ship	ICOADS (monthly) (Nassar et al. 2010)
Chemical source	GEOS-Chem-V8.2.1 (Nassar et al. 2010) (monthly)
Plane emission	GEOS-Chem-V8.2.1 (Nassar et al. 2010) (monthly)
Chemical surface	GEOS-Chem-V8.2.1 (Nassar et al. 2010) (monthly)

- P4503: The term “jack-knifing” is not clear to me, so I think other readers would benefit from a brief explanation at least, but as mentioned above, more details on obstacles to combining NIR+TIR here could potentially be very helpful for the CO₂ retrieval community.

I have changed ‘jack-knifing’ to ‘vertical oscillations’ with some explanation. A few comments on the obstacles to joint retrieval are followed with that. Page 4503, L17:

‘Note that ultimately we do not use the full profiles for this study as we find that spectroscopic or other errors introduce vertical oscillations into the estimated profiles with larger values than expected in the upper troposphere that are compensated by lower values than expected in the lower troposphere. The same effect is found in the GOSAT CO₂ retrievals as discussed in O’Dell et al. (2012). This vertical oscillation is one of the potential issues in joint retrievals by combining NIR and TIR radiance in addition to the limitation of the coincident measurements from two different instruments. However, the total columns of these profiles are still good estimates with well-characterized errors as discussed in section 5.1. Therefore, the profiles are mapped into column amounts and are shown to be consistent with the results of Wunch et al. (2011a). We use the profile retrieval instead of the Wunch et al. (2010) column scaling retrieval in order to understand the error characteristics of the CO₂ retrieval.’

- P4506, line 10: “(or)” should be removed

Fixed. Thank you.

- P4508, line 14 and P4514, line 12-13: grammar issues

Fixed as below:

'There are about 3 to 5 aircraft derived profiles per month excepted during September and October. Unfortunately there are no usable profiles for September and October that can be compared to TCCON because of cloudy conditions.'

'Which term contributes to the uncertainties will be discussed in follow.'

- P4515, line 7: Is the assumption of free-tropospheric CO₂ being well-mixed valid over land? Wofsy et al. (2011) HIPPO measurements are predominantly over the Pacific.

Yes, the aircraft measured CO₂ profiles over SGP site do suggest the vertical gradient is small between 600 hPa and tropopause, for example, three profiles measured by Learjet on July 31, August 2 and 3, which measured up to 10 km (Fig. 4 in old version or Fig. 5 in new version). We address this comments in the paper as below:

'Several aircraft only measure CO₂ up to approximately 6 km, but three of them go up to 10 km or higher, which are measured by Learjet on July 31, August 2 and 3 (Figure 5). These three profiles show that the free troposphere is well mixed and the vertical gradient is small (Wofsy et al., 2011), less than 1 ppm/km on average between 600 hPa and tropopause. Therefore, the lower part of x_{FLT} is from the direct aircraft measurements. Above that, the TCCON *a priori* is scaled to the measured CO₂ values at the top of the aircraft measurement so that the profile is continuously extended up to 71 km.'

- Table 1 caption: "imperial" should be "empirical".

Fixed. Thank you.