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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Towards constraints on fossil fuel emissions from total column carbon dioxide" *by* G. Keppel-Aleks et al.

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We thank the reviewer for her/his thorough review and address her/his suggestions below.

This study investigates the fossil fuel signal in total column CO2. A method is proposed for detection and quantiïňĄcation of regional scale fossil fuel signals. This is very relevant in the context of current and planned satellite missions for space borne CO2 monitoring. The manuscript reads very smooth. The authors do a nice job explaining the factors that are of relevance and may inïňĆuence the results in a way that might limit the observational constraints on fossil fuel. It is not clear, however, how these complications work out for the current analysis and whether what is derived from

GOSAT has really anything to do with fossil fuel CO2 in the end. In my opinion further efforts in this direction are needed as explained below.

It is mentioned in the introduction that for emission monitoring a regional rather than a city-scale approach as needed to allow bridging the scale gap from the city scale to the national scale. Although this sounds quite reasonable, it introduces a very important complication. At the city scale one can be conïňĄdent that the CO2 contrast is due to fossil fuel, on the regional scale, however, this is much less clear. For example, the inïňĆuence of biosphere emissions is mentioned several times, but the potential role of it in the analysis of the GOSAT data remains unclear. Some information can be derived comparing Table 2 (XCO2,fossil) with Table 3 (XCO2). For China I calculate a fossil contribution of 50%, but whether this is a lucky or unlucky shot is unclear. I recommend adding these percentages in Table 3 to get a better feeling. With biosphere contributions as high as 50%, and other factors complicating the comparison in this table, the agreement between model and GOSAT on sub ppm levels is actually amazing (bottom right part of the table). Is it right?

We agree with the reviewer that regional scale monitoring is more complicated than urban scale monitoring due to the fact that spatial and temporal variations may be attributable to natural flux, rather than anthropogenic, patterns. However, emissions verification at national scales will eventually require harmonization between the large fossil signals in megacities and larger urban areas, and smaller signals contained in CO2 observations elsewhere, as we indicate in the introduction. We have taken the reviewer's advice and included the fossil fuel CO2 contrast for the AM2 simulations in Table 3. The relative agreement seen in Table 3 for the regionally and seasonally averaged GOSAT observations suggest that our strategy to average CO2 along isentropes does indeed minimize the biospheric contribution to the signal and reveals the fossil signature.

It is concluded that fossil fuel leaves a discernable signature in total column CO2. However, the question is what is needed for emission monitoring. This should obviously only be a small fraction of the signature itself. It quickly bring the accuracy requirements down to something like a tenth of a ppm, which seems out of reach given inïňĆuences of the biosphere, sampling biases, aerosols, etc. In the end the reader is left with the question if the method that is proposed in this study is really viable. It would be instructive to have a table providing an approximate error budget of the various inïňĆuences that play a role.

Given the inherent sources of error identified by the reviewer the fact that the simulated and observed XCO2 contrasts are in reasonable agreement suggests that the method we present in the paper is viable. Retrieval algorithms for the GOSAT data are being improved by several international research groups, and new satellites with smaller footprints and therefore less susceptibility to sampling bias and aerosols, are being developed as stated in the discussion section:

"Although the initial comparison presented here between simulations and observations demonstrates that estimating fossil fuel emissions from space will be difficult, our results provide direction for making X_{CO_2} a more useful observation for validating fossil fuel emissions. Both the sampling bias in AM2 (Table 3) and the cloud bias (Fig. 6) point toward footprint size as a key design factor in the utility of satellite observations for fossil fuel emissions monitoring at policy relevant accuracy. OCO-2 or CarboSat, whose footprints are 40 and 20 times smaller than that of GOSAT, may be an easier data set from which to diagnose fossil emission trends as the likelihood of cloud-free scenes will be greater and the spatial coverage will therefore be more complete."

We also discuss that ancillary observations will be necessary for disentangling the various processes affected variations in CO_2: "Techniques such as data assimilation or flux inversions should provide more precise flux estimates and will be necessary to account for interannual variability in natural CO_2 fluxes, which we have ignored in this

analysis. Moreover, analysis of how concomitant changes in land fluxes and ocean fluxes will accompany decadal-scale increases in fossil fuel emissions is necessary as coherent regional changes may obscure detection of fossil signatures. The methodology presented in this paper does represents one tool that can be used in conjunction with other observations at other spatial scales to move toward national-level emissions verification."

I am surprised by the sign of the clear sky bias as discussed on page 29896 and shown in ïňĄgure 6. Why would the fossil fuel contrast be systematically low under cloud free conditions. The subsidence / low wind speed conditions in high pressure systems rather tend to build up pollution in source regions. This would rather lead to a high bias when considering clear sky only. A low bias reminds rather of the biosphere sequestering carbon under sunny conditions, or the variability that is correlated with potential temperature. I conclude that the clear-sky bias in the XCO2 contrast has little to do with the clear-sky bias in XCO2,fossil contrast. Besides this, a related bias seems to have been overlooked, which comes from the fact that if the fossil signature is easier detected outside the growing season, this coincides with the season when fossil fuel emissions are usually higher than average because, for example, of domestic heating during winter.

We agree with the reviewer that the lower residence time of fossil fuel CO2 in the source region during low pressure/cloudy conditions should lead to a positive bias when considering only cloud-free conditions, and have added a sentence to the Results section to indicate that, "We recommend that the bias from cloud cover be investigated in a transport model that includes both anthropogenic aerosols and interactions between meteorology and biospheric fluxes." As discussed in the text, the biospheric fluxes underlying AM2 do not respond to meteorology and therefore enhanced biospheric uptake under sunny conditions does not affect the regional contrasts. Likewise, the small bias in the east-west contrasts when considering only cloud-free scenes is sim-

ilar whether using fixed averaging regions or averaging regions defined by potential temperature.

Looking at the noise in Figure 3, I'm wondering how sensitive the average is to the westward extension of the source region. The numbers in the caption should mention also the uncertainty of Table 3. It is only in comparison with the signiiňĄcance of the mean that the partial sentence 'although the individual retrievals are quite variable' makes sense. Looking at Figure 3 I iňĄnd it actually hard to believe that the uncertainties of the GOSAT derived mean contrasts are really so low. Looking at the zero uncertainties listed for Australia I don't even understand how they were derived. Else, what is missing is a comparison of the size of the inferred fossil fuel signatures with what has been published by others in the past (Kort et al, for example).

The error estimates in Table 3 represent the standard error of the mean, and we have added a sentence to the caption to reflect this. We have also added the error estimates from Table 3 to the Figure 3 caption. O'Dell et al. (2012) have found that ACOS-GOSAT retrievals have single sounding precision of 1-1.5 ppm, so averaging 50-100 retrievals over Australia, with small fossil fuel emissions and biospheric fluxes, has lead to the standard error on the mean contrast of less than 0.05 ppm reported in Table 3.

We have added a sentence the introduction to indicate the magnitude of the fossil fuel signature observed over megacities: "Results from Los Angeles suggest that fossil fuel enhancements over a megacity are large enough (around 3 ppm) to be observed in the total column (the vertically integrated mass of CO_2 in the atmosphere above a given location) via satellite observations (Wunch et al., 2009; Newman et al., 2012; Kort et al., 2012). "

We have also added a sentence to the results section to put the magnitude of the regional contrasts in context of what is seen over megacities:

"The regional contrasts are smaller than those expected over locations with concen-

trated emissions, such as megacities, which show enhancements of $\sim$3 ppm (Kort et al., 2012)."

29891, L13:a' where available' between comma's 29894, L11: 0.2 instead of 0-2

We have made the corrections.

29896, L14: It is not clear why aerosol should reduce the contrast. At the surface albedo of urban centers it seems more likely that aerosols cause overestimation of retrieved XCO2, which would increase the XCO2 contrast. 29899, L3: The point about bias correction is well taken, but the evidence may be circular in the case of ACOS since it is based on transport models.

If high aerosol optical depth is spatially correlated with high XCO2, then discarding scenes with high aerosol loading would reduce the contrast in XCO2. However, not all scenes with high aerosol loading will be discarded, and aerosol may bias the retrieved XCO2 in either a positive or negative sense. We therefore have changed the text:

"AM2 does not include aerosols, which, at high optical depth, would limit satellite retrievals similarly to clouds. Since $CO_{2,\text{fossil}}$ and aerosol share anthropogenic sources, high $X_{CO_2,\text{fossil}}$ and high aerosol optical depth may be spatially correlated which could lead to further bias in the regional contrasts."

Table 1: Why not use degrees West for the US? Figure 6: 'Fraction' instead of 'Fracion'

We have made the revision.

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