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Atmospheric Chemistry and Physics Discussions

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Interactive Comment

Interactive comment on "Global carbon monoxide products from combined AIRS, TES and MLS measurements on A-train satellites" *by* J. X. Warner et al.

J. X. Warner et al.

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We wish to thank reviewer #2 for the valuable comments. We have responded to all of the reviewer's points with each reply starting with "ANSWER:" We believe this paper and the related study has benefited from the reviewer's comments. Finally, we also appreciate that this reviewer recognizes that "this improved analysis is potentially useful for studies of CO, in particular, and atmospheric chemistry in general."

Interactive comment on "Global carbon monoxide products from combined AIRS, TES and MLS measurements on A-train satellites" by J. X. Warner et al. Anonymous Referee #2 Received and published: 13 August 2013

General Comments The manuscript present a data fusion methodology applied to combing AIRS, TES, and MLS CO retrievals. The methodology is similar in form as the Kalman filter. The analysis is then compared to independent CO profiles from 2 field campaigns (INTEX-B and HIPPO). Results show improved analysis and highlight the complementarity of these retrievals. This improved analysis is potentially useful for studies of CO, in particular, and atmospheric chemistry in general.

However, I have several concerns with regards to the technical details of the methodology. I find the manuscript to lack the necessary details on the observation operator, H in the Kalman filter equation. I also find the manuscript to lack some discussion on the validity of several assumptions critical for an effective data fusion, and useful for easy interpretation of the analysis. In particular, Id like the authors to elaborate on the following issues:

1) Collocation. I understand that the retrievals are 15-30 minutes apart. Is the variability in CO small enough at this spatio-temporal time scale? If not, how is the difference in location and time between retrievals handled in the filter?

ANSWER: We use collocated AIRS and TES (or MLS) pixels since all three sensors are part of the A-train satellite constellation. The tracks of TES (and MLS) are the same as those of AIRS and their pixels collocate with AIRS nadir pixels. The time difference between these collocated measurements is approximately 15 to 30 minutes. The variability in CO is small in this time frame considering the spatial distributions of the CO plumes are associated with mesoscale weather systems due to transport.

We have changed the sentence as: “We do not attempt to evaluate any time variability in the CO filed, but to simply combine CO of collocated pixels from AIRS, TES, and/or MLS that are part of the A-train satellite constellation and are measured within a short time period (15 – 30 minutes).”

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Are the spatial error correlations between observations (between 2 TES retrievals for example) handled as well?

ANSWER: No, we did not consider the spatial error correlations between observations and assumed the observation error covariance R as diagonal. See explanation below in our answer for 2) a).

2) Observation error covariance, R.

a) In Line 1 p 15416, it is assumed that R is diagonal. I assume that R is a retrieval error covariance matrix of TES or MLS in this case. And the elements of this matrix is the error covariance of a retrieval at a certain vertical level of the retrieval grid with the retrieval at a different vertical level. As I understand it, R in TES and MLS is not strictly diagonal (in fact the errors are particularly correlated in the vertical). And so, what justifies the diagonal assumption?

ANSWER: We added the following in the text: "In data assimilation, including that applied to trace gases, it is often a standard assumption to use a diagonal R matrix, which assumes that there is no vertical or horizontal correlation between different observations (see Stajner et al., 2001 and Tangborn et al., 2009). We realize that including observation error correlations would have the effect of reducing the relative impact of each individual observation slightly (depending on the correlation), and its omission here does slightly degrade the accuracy of the final data set. However, the purpose of this work is to demonstrate the viability of the data fusion approach to combining satellite data sets, and future enhancements to this work will include a more refined observation error covariance."

b) In Line 15 p 15417. What is the rationale behind using one global set of error profiles? Should the errors be scene-dependent?

ANSWER: We added this discussion in the text by replacing "We then adjusted these profiles to reduce prescribed errors for AIRS in the mid troposphere and for TES in the

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lower troposphere. This is based on previous knowledge and validation experience, which shows it is reasonable to place more emphasis on TES data in the lower troposphere and AIRS data in the mid-troposphere." with "Three dimensional retrieval errors are difficult to quantify due to limited amount of in situ measurements in both temporal and spatial dimensions. The retrieval errors distributed by the individual teams (AIRS and TES in this case) are defined and computed differently, which means they cannot be used together. We used the statistics of the validation summaries from various studies to derive one global set of error profiles (Luo et al., 2007; McMillan et al., 2011; Warner et al., 2007 and 2011; Yurganov et al., 2008) to reduce prescribed errors for AIRS in the mid troposphere and for TES in the lower troposphere. Additionally, we considered the statistics of the averaging kernels (AKs) from AIRS and TES to weight the relative importance of the data in the vertical dimension. We have found that constructing the global error profiles from our experience of validation and the retrieval AKs provides a better estimate than the errors distributed by the retrieval teams."

3) Retrieval bias. In Line 26-27 p 15415, it is also assumed that the retrievals are unbiased. I believe this is not the case for both TES and MLS and AIRS CO. What justifies this unbiased assumption? This especially has an impact if both retrievals are biased on the same direction.

ANSWER: This study aims to combine two satellite products of the same species without altering any remote sensing measurements in post processes. Additionally, the observations (TES and MLS) are global datasets that match well with AIRS in both temporal and spatial spaces. Also, as discussed earlier, it is difficult to quantify errors and biases for global and multi-year satellite trace gas products due to the lack of the availability of in situ measurements. This is a proof-of-concept paper and as a first approximation we assume no bias. This assumption is often made in DA (e.g. the bias between observations assimilated may not be known). The good comparison of the analyses with independent data would indicate this assumption is not deleterious.

We do believe that localized biases exist between AIRS and TES and between AIRS

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and MLS; however, there have not been enough studies that clearly define the CO retrieval biases globally for AIRS and TES/MLS compared to the truth. To demonstrate the robustness of the data fusion system, we have tested the correction based on the differences between AIRS and TES at 500 hPa. This is a quick test to answer the reviews and we will not seek to use the conclusions in the final paper. The detailed studies in regards to the retrieval biases, and the bias correction thereafter, are needed in follow up studies.

Figure 1 shows the averaged monthly mean bias between TES and AIRS at 500 hPa for March 2006 to be -10 ppbv (TES-AIRS) based on the difference histogram without bias correction (top panel). We apply the bias correction in AIRS background field and the resulting new histogram is shown with bias correction (bottom panel). The new analysis results are shown on the left middle panel in Figure 2b, which is similar to Figure 2a (same as Figure 5 in the manuscript) except it is for before the bias correction. As expected, the global mean of the TES minus AIRS at 500 hPa is nearly zero (right bottom panel) and so is that of the analysis increment at 500 hPa approximately (left bottom panel). However, the analyses CO are in general too low in the NH lower troposphere even though the analysis increment is higher. This negative impact of the bias correction is largely due to the fact that we are using a global constant bias. This can be improved as multi-dimensional bias profiles are used, once the better error and bias information is available.

We have added the following sentence in the discussion of the bias in Sect. 3: "Results from a bias correction experiment where a crude approximation to the global bias between AIRS and TES CO is made (not shown), indicate that the assumption of no bias does not affect the data fusion results adversely."

4) Background error covariance, Pb.

a) In line 9-11 p 15416, it states:

"The background error covariance Pb, consists of not only the correlation information

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between any two variables (at different locations) in the background state vector, but also the covariance matrices of the AIRS retrievals."

Pb = sqrt(D) x C x sqrt(D)

where C is the matrix containing the correlations and D is the matrix containing the variances of the analyzed species (El Amraoui et al., 2004). Here C stands for the covariance between two grid points. We model the terms of C with the quantity Ci,j =. . . are the standard deviations of background error at location i and j respectively, h is the horizontal correlation model, and v is the vertical correlation model.

Please rephrase since Pb is in fact a function of the correlation matrix and the variances. Is the error covariance matrix of the AIRS retrievals equal to Pb?

If not, why is it not used in Pb? How is it incorporated in the filter?

b) What exactly is C? is C the error correlation matrix? If yes, the definition of Ci,j is erroneous (it should be Pb(i,j) since ph*pv is C and si and sj are the diagonal elements of D.

ANSWER: We made a mistake on the variable notation in the text. We put Ci,j where it should have been Pbi,j. We also corrected "covariance" in places where it should have been "variance". In addition, "error" is added where it's appropriate.

The Pb we used does not equal to the error covariance matrix of the AIRS retrievals; it is estimated (see below).

See the revised text below: The background error covariance Pb is constructed from the error correlation matrix between any two locations in the background state vector and the error variances of AIRS retrievals. It is defined as:

Pb = transpose(sqrt(D)) x C x sqrt(D) (3)

where C is the error correlation function and D is a diagonal matrix containing the error variances of the analyzed species (El Amraoui et al., 2004). Following a general approach in data assimilation, we separate the vertical and horizontal correlations (Daley and Barker, 2000). The correlation is equal to the product of the horizontal correlation h, and the vertical correlation v. The equation for a component of Pb is:

Pbij= σiσjhv

where σi and σi are the standard deviations of background error at location i and j respectively, h is the horizontal correlation model, and v is the vertical correlation model.

It appears from the definition of C(i,j) that the vertical and horizontal error correlation is assumed to be uncoupled. What justifies this assumption? Also, what is the rationale behind choosing a power law function for ph? Errors in CO are in fact anisotropic.

ANSWER: Yes, we assume the vertical and horizontal error correlation as uncoupled. We chose to separate the error correlations to be convenient for further testing. We also believe the CO error field is more isotropic than anisotropic. We chose to use the Power law function (Dee and da Silva, 1999) also based on the fact that the decaying of the error from the center is slow and broad.

5) Observation (or forward) operator, H. Characterization of this matrix is critical in ‘transferring’ information in any data fusion. Please discuss how H is constructed. Are the associated retrieval averaging kernels and priors incorporated in H? If not, why aren’t they? I believe this is an important information to know from the users perspective in order to help the users of this analysis to better interpret and better understand how to properly use it for their purposes. Does H include mapping to AIRS grid as well? How is this done for TES and MLS?

ANSWER: For H, we have constructed a nearest neighbor interpolation in lat, lon, and pressure. The transpose of H is in fact the mapping from TES/MLS to AIRS and it is only used in K in eq. (2).

We incorporated the retrieval averaging kernels (AKs) and priors implicitly, because we used the total errors from the retrievals that include the smoothing errors, which is

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associated with the AKs and priors (Rodgers, 2000). Additionally, we have weighted AK information in the prescription of the error profiles. See also answer for question 2) b). Again, this is a proof-of-concept paper and the good comparison to independent data is good evidence that this approach is not deleterious. Future studies will include detailed tests on how to incorporate the AKs.

6) Analysis diagnostics. It would be very informative if the averaging kernels of the analysis are shown – since this is the crux of the data fusion. This will greatly support and better elucidate the comparison with independent data.

ANSWER: We agree, however, at this stage of the study, this is very difficult to carry out due to the complexity of the problem. Further studies are needed and they will be the subjects of future publications. For now, to compare the data fusion results with other data (in situ, models, etc.), we recommend the users to convolve independent data with AIRS and TES AKs independently and then compare with the fused dataset.

Specific Comments 1) Line 17-18 p 15411. The improvements shown in the Abstract are not explicitly stated in the text.

ANSWER: We added a sentence in line 28 on page 15421: "These error reductions represent 20 to 30% of the CO VMRs especially in the SH.". We have also added "($\sim$20%)" in line 23 on page 15422 after "by approximately 10 to 20ppbv."

2) Line 17-27 p 15413, Line 1-17 p 15414. It would be informative if the associated biases of these retrievals (if there are) are explicitly stated as well.

ANSWER: We added the sentence in line 5 on page 15414: "Validations and intercomparison between AIRS and TES CO indicate that localized biases exist (Warner et al., 2010), which globally and annually generally cancel each other to a large extent." See also the discussion of bias correction in question 3). AIRS is a nadir sounder that does not provide accurate measurements in the UTLS regions as a limb sensor such as MLS. There would have been no point to establish a bias study because of the

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different vertical location of the measurement and observational characteristics.

3) Line 8-9 p 15415. ‘The population of the profiles on the horizontal plane is determined primarily by the observed variances’. Please elaborate or rephrase.

ANSWER: We have removed this sentence. The algorithm section describes what this sentence was intend to convey.

4) Line 14-15 p 15415. ‘. . .but rather uses AIRS continuous measurements. . .’ Please elaborate on the use of the word ‘continuous’.

ANSWER: We have changed the word ‘continuous’ to ‘routine’.

5) Line 24 p 15415. ‘i.e. the current size of the AIRS vector’ Is this vector the state vector in AIRS CO retrieval? Please specify. Also, does the AIRS CO state vector include non-CO state variables like emissivity and surface pressure, etc? If yes, is this part of the state vector as well? How do you handle this in H?

ANSWER: Yes, there are non-CO state variables in AIRS retrievals, but they are not used here. The H operator only contains CO.

6) Line 24 p 15418. ‘Observation Minus Forecast (OMF)’. I suggest modifying this terminology to an appropriate term to fit the data fusion approach of this study.

ANSWER: We changed OMF to TMA (TES Minus AIRS) in the text and figures and captions.

7) Figure 1. Equ?

ANSWER: We have replace “Equ.” with “process”.

8) Figure 5. Please increase font size and specify units in the caption

ANSWER: Corrected.

9) Figure 6&7&8 Please specify the units.

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ANSWER: Added “VMR (ppbv)” after all “CO”.

Added Reference:

Stajner, I., RiishÂÍojgaard, L. P., and Rood, R.B.: The GEOS ozone data assimilation system: Specification of error statistics, Q. J. Roy. Meteorol. Soc., 127, 1069–1094, 2001.

Tangborn, A., Stajner, I., Buchwitz, M., Khlystova, I., Pawson, S., Hudman, R., and Nedelec, P.: Assimilation of SCIAMACHY total column CO observations; Global and regional analysis of data impact, J. Geophys. Res., 114, D07307, doi:10.1029/2008JD010781, 2009.

Interactive comment on Atmos. Chem. Phys. Discuss., 13, 15409, 2013.

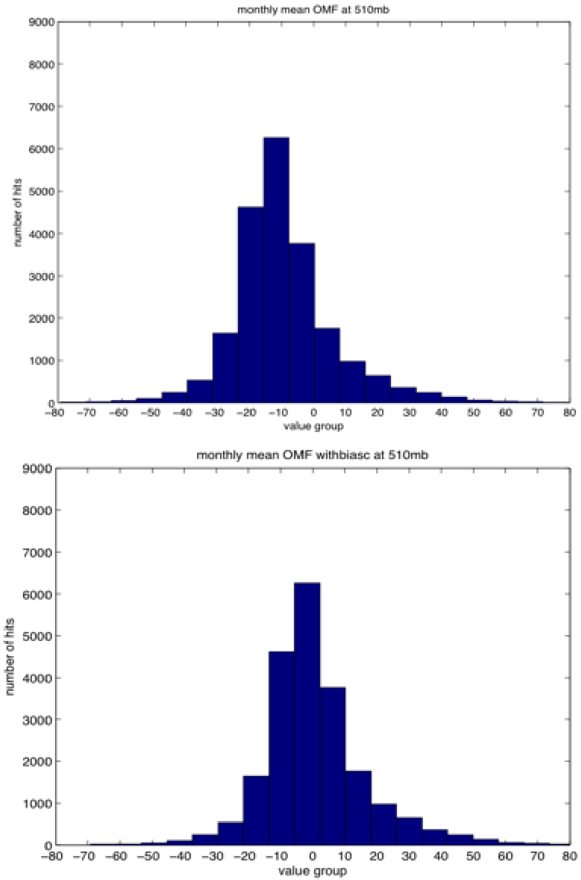

Fig. 1. Fig. 1. Histograms of TES – AIRS CO VMR differences (ppbv) for before the bias correction (top panel) and with the bias correction (bottom panel).

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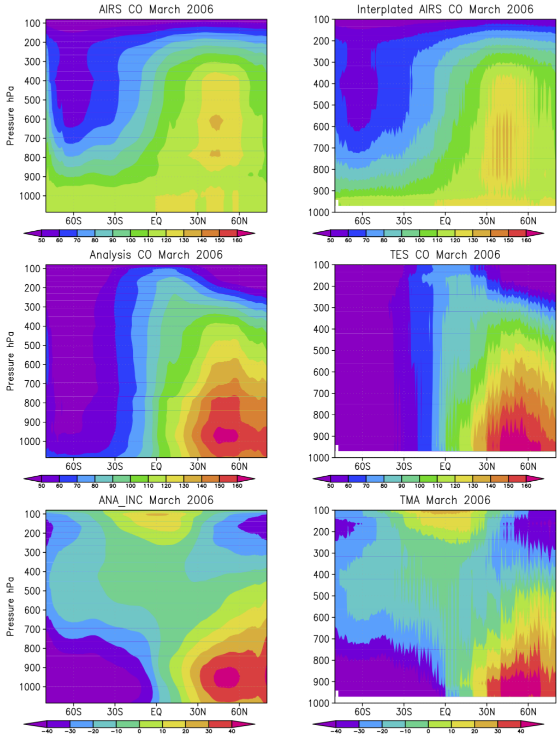

Fig. 2. Fig. 2a. Grid averaged monthly zonal means with AIRS CO (left top panel), analysis CO (left middle panel), analysis increment (left bottom panel), AIRS CO interpolated to TES location (right top panel

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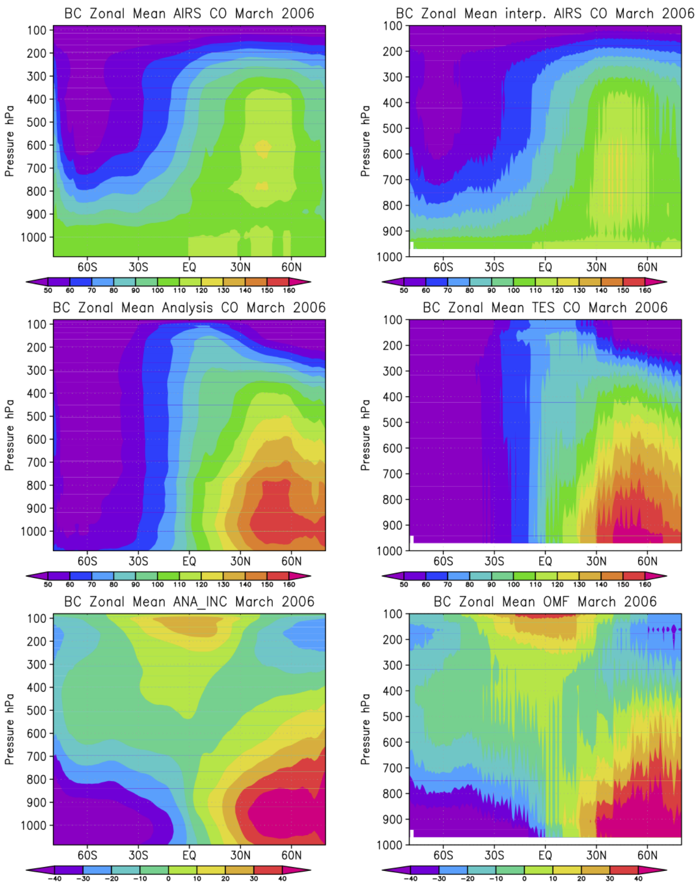

Fig. 3. Fig. 2b. As Fig. 2a, except with bias correction

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