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Atmospheric Chemistry and Physics Discussions

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

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We appreciate very much reviewer #1's comments. We have answered all questions; with each answer starts with "ANSWER:" We received the same comments from this reviewer before the publication of this manuscript on acp-discussion and made necessary revisions. We are answering all the comments again to publish as reply to reviewer's comments, however, pointing out the previously corrected comments as "No longer relevant".

—- 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 #1

Manuscript of Warner et al. "Global Carbon Monoxide Products from Combined AIRS, TES, and MLS Measurements on A-train Satellites" introduces a potential methodology to combine satellite datasets from nadir- and limb-viewing CO sensors that measure radiances in the thermal infrared and microwave spectral windows. Timeliness to create the unified global CO product in the troposphere and lower stratosphere is motivated by availability of six space-borne instruments that report CO products (MOPITT, AIRS, TES, and IASI- TIR CO data; MOPITT – NIR CO data; ACE and MLS –CO profiles). The thermal infrared nadir-viewing sensors (MOPITT, AIRS, TES, and IASI)) with DFSâĹij0.5-1.5 provide information on the partial CO columns in the mid- and upper troposphere, while TES, IASI- TIR CO data; MOPITT – NIR CO data; ACE and MLS –CO profiles). The thermal infrared nadir sensors (MOPITT, AIRS, TES, and IASI) with DFSâĹij0.5-1.5 provide information on the partial CO columns in the mid- and upper troposphere, while the near-infrared channels of MOPITT and SCIMACHY report column-based CO with DFS âĹij1. Information on CO profiles in the upper troposphere and lower stratosphere is presented by ACE and MLS CO limb retrievals. Indeed there is a tendency to perform the multi-sensor CO and ozone data fusion studies without help of assimilation of these data in the chemistry-transport or chemistry-climate models governed by meteorology of NWP systems. Study of Warner et al. represents this tendency, assuming that AIRS CO measurements can be considered as the background field, while TES and MLS CO retrievals can be analyzed as observations and improve the AIRS-CO background. Motivation for this "is simply combine a number of measurements taken within a short time period (15 - 30 min)" using framework of the optimal interpolation (OI) by weights expressed by errors of retrieved CO. This OI-technique is referred by authors as the Kalman Filter method (without 'transport by the model dynamics'). The 'transport by the model dynamics' is replaced by continuous high density AIRS CO retrievals that can constrain (resolve) only partial CO columns as shown by AIRS kernels.

Three main results of this data fusion study for AIRS-CO as a background state are: 1) "higher spectral resolution of TES" helps "to extend AIRS CO observational sensitivity to the lower troposphere"; 2) "combined CO measurements from AIRS and MLS provide enhanced information in the UTLS"; 3) combined CO "show improved sensitivities in the lower and upper troposphere (20-30% and above 20%, respectively) as compared with AIRS-only retrievals".

As a reviewer I have several questions and concerns on the method employed in this data fusion study with AIRS-TES and AIRS-MLS.

1. Methodology of data fusion using OI techniques without use of 'unified analysis space', such as CO forecast space, can be applied to the data with comparable vertical resolutions and persistent data-data differences should be identified before the multi-sensor data fusion. Authors mentioned only that 'we assumed that there is no global bias in CO between AIRS and TES." The use of AIRS-CO as 'unified' space with DFS < 1 (or vertical resolution that corresponds to column-based estimates) is a bit confusing. All vertical structures of AIRS-CO should be represented at least by time-variable 3D a-priori to proceed towards data fusion with other CO products.

ANSWER: We used a 3D space with fixed vertical grids and varying horizontal locations provided by AIRS L2 products in this data fusion study. The only analysis space that we do not use compared to the traditional data assimilation is the time/forecast dimension. Although, of course, the AIRS L2 products do evolve in time, as the observations are made at different times, and this is reflected in the data fusion procedure. The detailed vertical resolutions for AIRS, TES, and MLS are discussed below in Question #4.

Although AIRS CO DOFS, the trace of the averaging kernels, is approximately less than 1, retrievals at each vertical grid (from a total of 60 levels) are given that provide some degree of independent information. The relatively low DOFS values for AIRS CO (or any other thermal nadir-viewing sensor) only highlight the need for data fusion with

other products, such as those from a limb-viewing sensor.

AIRS CO retrievals are based on one global a priori (or first guess) profile, not 3D simulations from a model, which is to emphasize that any variability in the AIRS CO products is from true measurements. For the purpose of this study, we have shown that the AIRS L2 retrievals provide time-variable 3D CO distributions that are sufficient to serve as background values.

We assumed there is no large global CO bias between AIRS and TES because the differences between the two datasets are varying with location and time. Bias is very difficult to evaluate between retrievals (because they have different characteristics such as different Aks, spatial resolution and so on). We assume that bias of the retrievals is removed or weak compared to the truth because each dataset is validated against in situ data (see references in the text: Luo et al., 2007; McMillan et al., 2011; Warner et al., 2007; Livesey et al., 2007).

Note, we have added the reference by McMillan et al. in the text.

2. Resolutions and information contents of AIRS-CO (DFS <1) and MLS-CO (DFS âĹij10) are different. Analysis of MLS-CO with kernels is justified for constraining CO predictions by models in the UTLS. It is difficult to interpret what is MLS-CO constraining for CO-background represented by AIRS-CO retrievals with DFS <1.

ANSWER: We are not clear about the point of the referee. The MLS-CO constrains the AIRS-CO by apportioning the AIRS-CO information in the vertical.

3. In the nadir view TES and AIRS should have in general similar vertical resolution and sensitivity. I'm not aware about the limb CO measurements by TES. ("The Aura limb sounders (TES and MLS), on the other hand, possess the advantage of high vertical resolution in the UTLS region but lack horizontal coverage"). Before combining AIRS and TES CO-TIR data the instrument biases should be properly addressed (corrected) to avoid "biased" data fusion. The 'enhanced' sensitivity of TES in the lower tropo-

sphere is a surprising result for TIR-CO retrievals. It reminds the enhanced sensitivity of MOPITT-V3 CO retrievals with the dominant surface kernel. This feature was a bias of CO in MOPITT-V3 data. Bias was corrected in the next MOPITT versions (V4 and V5).

ANSWER: We only used TES CO products in the nadir views. The satellite nadir viewing thermal sensors do, in general, provide similar vertical resolution and sensitivity; however, the spectral resolution does make a difference in the hyperspectral measurements. We accepted TES CO as validated products and used the errors provided by the TES team accordingly. The point about the bias is addressed in #1 above.

4. Technical comment: It is not clear how resolution (averaging) kernels of TES, MLS and AIRS and their a priori information were included in the 'sub-optimal' Kalman Filter analysis. Averaging kernels of MLS and TES data are parts of the observation operators H in (1)-(2). Discussions on error specifications by CO retrieval errors of AIRS, TES, and MLS and introduction of vertical correlations (0.17) provide a hint that CO retrievals are considered as conventional data without effects of kernels.

ANSWER: The proper inclusion of the averaging kernels in the observations addresses the smoothing errors in the retrievals (Rodgers, 2000). We included the total retrieval errors from AIRS and TES as a ratio in the R matrix in Equation 2. This way the effects of the averaging kernels, the smoothing errors, are already taken into consideration.

There is no information/discussion on the vertical resolution of combined CO products in the text (except Figure 2b).

ANSWER: We have stated in the Methodology Section: "The analysis state vector Xa is the new estimate of the state vector, which has the same dimension as the background field (Xb), i.e., the current size of the AIRS vector. The size of the observation vector Xo is determined by the number of assimilated observations (TES or MLS)."

We also added the following discussion about the vertical resolutions:

"The vertical resolution of the analysis for the combined AIRS and TES CO is based on the AIRS pressure grid in the troposphere; whereas the vertical resolution of the analysis for the combined AIRS and MLS CO is based on the AIRS pressure grid in the stratosphere and the UTLS regions. Table 1 lists all the pressure levels used in the AIRS and TES combined CO experiments (left columns) and the AIRS and MLS combined CO experiments (right columns). These analyses pressure levels are fixed except for near the surface."

1) Scientific Significance Idea to perform multi-sensor data fusion of CO observations and create unified CO data set on 1-deg. horizontal resolution is very important for evaluation of chemistry climate models, however the vertical resolution of combined CO product is not clarified and discussed.

ANSWER: The vertical resolution is discussed in the answers for Question #4 above.

2) Scientific Quality Main questions to scientific approach and applied methods are listed above. Appropriate references are in the text. It would be useful to discuss what is a scientific quality of combined and 'individual' products of CO for model assessments?

ANSWER: We agree with this reviewer's comment on the discussion of the scientific quality using the combined and 'individual' products to assess models. To accomplish this, we need to carry out data assimilation for the combined and 'individual' products using models. In fact, we have been pursuing funds for this project, and we hope the outcome of the study will be published at a later time. Although the suggested discussion is useful, it is beyond the scope of this paper.

3) Presentation Quality Presentation and illustrations reflect major ideas, method and results. Several samples of sentences that need clarifications and corrections (typos) are below.

Page 6: "This system does not require a model to constrain the physics of the geo-

physical fields, but rather uses AIRS continuous measurements to constrain the spatial and temporal variability of the TES and MLS measurements."

ANSWER: We think the phrase is appropriate and we do not understand what the referee is referring to.

Page 7: "Assimilating one set of observations into another presents an opportunity to gain some insight into satellite error correlations."

ANSWER: No longer relevant. Removed before publishing on acp-discussion.

Page 8: On error characterization "Figure 3 shows the prescribed error 1-sigma standard deviations (SDVs) for AIRS as the background error and for TES as the observational error. "

ANSWER: No longer relevant.

Style and typos: Title: Global Carbon Monoxide Products from Combined AIRS TES and MLS (comma.. AIRS, TES...)

ANSWER: No longer relevant. Corrected before publishing on acp-discussion.

Abstract: "The combined retrievals from the data fusion technique ....." should be revised

ANSWER: No longer relevant. We changed above to the following before publishing on acp-discussion: The data fusion results . . .

Page 8, (Dee and da Silvar, 1999) => (Dee and da Silva, 1999) ANSWER: No longer relevant. Corrected before publishing on acp-discussion.

"The pixel sizes are not to scale for the AIRS Field Of Regard (FOR) of ...." needs revision

ANSWER: No longer relevant. We revised above to the following before publishing on acp-discussion: “The pixel sizes do not represent the correct proportions of the sizes

for the AIRS Field Of Regards (FORs) at approximately 45x45 km2 and the TES Field Of Views (FOVs) at 5x8 km2.”

Page 9: "The distribution of the TES profiles in the horizontal plane is determined primarily by the observed variances from AIRS" . . .. needs clarification

"The variations measured by AIRS represent the background CO distribution in this approach and TES retrieved CO is considered as the observations as described in Section 3." . . . needs revision

ANSWER: No longer relevant. We revised the paragraph for the acp-discussion.

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