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Atmospheric Measurement Techniques Discussions

Interactive comment on "Evaluation of single-footprint AIRS CH_4 Profile Retrieval Uncertainties Using Aircraft Profile Measurements" *by* Susan S. Kulawik et al.

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Thank you to the reviewers for their helpful comments. The format of this response is alternating paragraphs of: reviewer comment, response, reviewer comment, response... The ordering of the responses are: major comments from reviewer 1, minor comments from reviewer 1.

Responses to Major comments from Reviewer 1:

Reviewer 1: 1-1) 3. MUSES-AIRS Optimal Estimation of CH4 from single-footprint, original (non cloud- cleared) AIRS radiances:, page 5, "Good quality and sensitivity

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Discussion paper

flagging for AIRS CH4:" 1-1) The authors should give more explanations on the quality flags which they have applied to AIRS CH4 data. Are "radiance residual rms and mean" for all wavelength regions used in the AIRS CH4 retrieval? What are "NESR", "|KdotdL|", and "TSUR"? These terms may be referred to in some previous papers describing AIRS CH4 retrieval algorithm, but the authors should at least spell them out and give their definition.

Response: A description of the quality flags was updated and a references given that defines and describes each quality flag. Text added to the paper, "Quality flags are discussed in more detail in the Aura-TES user's guide (pp 27-30, Herman et al., 2018). The specific flags used for AIRS CH4 are as follows, which were set by minimizing the standard deviation of small clusters of retrievals and to standardize the sensitivity:"

Reviewer 1: 1-2) "Cloud OD < 0.3" means that clouds that partially exist in the AIRS FOVs probably affect the AIRS retrievals and the amount of the effects would vary depending on the cloud OD itself. How did the authors evaluate the effects in this research?

Response: A plot of error versus cloud optical depth was added to the supplement. Text added, "* Cloud optical depth < 0.3. This ensures that the cloud is not opaque and there is fairly uniform sensitivity so that the bias correction is fairly consistent. The bias versus cloud optical depth is shown in the supplement."

Reviewer 1: 1-3) How did the authors define tropopause height at each CH4 measurement location and calculate its tropospheric and stratospheric degrees of freedom? 1-4)

Response: The tropopause height was obtained from GMAO files. Text added to the paper after Eq. 2: "The degrees of freedom, DOFs, describing the sensitivity of x to the true state, and is equal to the trace of A_xx. The degrees of freedom in the troposphere is equal to the trace of the averaging kernel corresponding to the troposphere, and the degrees of freedom in the stratosphere is equal to the trace of the averaging kernel

corresponding to the stratosphere. The troposphere is defined using the tropopause height parameter from version 5 of the NASA Global Modeling and Assimilation Office (GMAO) Goddard Earth Observing System (GEOS-5) model (Molad et al., 2012)."

Reviewer 1: 1-4) What is "predicted error"? The authors discuss the "predicted error" in the later part of the text, but they should here mention the definition.

Response: The predicted error is the total error from the linear estimate, Eq. 4, and is a field in the output product. Text added to the paper after Eq. 7 "The square root of 7b is the predicted observation error.", and text added to the description of Fig. 3, "Figure 3 shows the predicted errors for the AIRS partial column XCH4 VMR within the pressure levels measured by the aircraft. The measurement error (light green) is 18 ppb (from the last term of Eq. 7b) , and the total error for a single observation (including smoothing error) is 41 ppb. A component of the total error, the cross-state error, is estimated as 21 ppb (from Eq. 7b)."

Reviewer 1: 2) 3.1 Retrieval Error Characteristics, page 6, Equation (2) The authors should briefly explain the definition of A_xy. In this case, x indicates a methane profile and y does simultaneous retrieved parameters such as temperature and there is no relationship (cross-term) in nature between methane and temperature.

Responses: Added in new text after Eq. 2 "Axx describes the dependence of x on the true state x, and Axy describes the dependence of x on the true state y, which is non-zero because of correlations in the Jacobians, K, for x and y."

Reviewer 1: 3) "3.2 Approach for Comparing AIRS measurements to aircraft profiles", page 7, Equation (4) In my understanding, A_cc is a symmetric matrix with a dimension of the number of atmospheric layers that can be observed by aircraft, while A matrix has a dimension of the number of full atmospheric layers from the surface to the top of the atmosphere. A_cs should be a non-square matrix, and how is it defined by the cross-terms of the A matrix? More explanation should be needed for readers.

Response: Added in new text after Eq. 4 "So, if for example, the aircraft measured pressures 0-9, and did not measure pressure levels 10-65, then Acc=A[0:9,0:9] and Acs=A[0:9,10:65], where A is the full averaging kernel."

Reviewer 1 4) "3.2 Approach for Comparing AIRS measurements to aircraft profiles", page 8, Equation (6) Sa matrix should in principle includes random errors only. The first term A_cb Sbb_a A_cb(T) comes from radiance biases that should have systematic characteristics. The other three terms or the second and the last terms only may be randomly distributed errors. Is it possible to treat errors that may have different characteristics in the same manner?

Response: Equation 6, as the reviewer notes, only addressed random errors. Added Equation 6a, which is the bias component of error, and Equation 6b, the current Equation 6, the variable component of the error. Added additional text to describe this. "Equation 6a represents the propagation of mean biases from: (1) fixed (non-retrieved) parameters, e.g. spectroscopy (b), (2) jointly retrieved parameters, e.g. temperature, (y), (3) "stratospheric", describing the impact of the part of the atmosphere not covered by the aircraft on the measured part (xs), or (4) measurement errors (n) into biases of xc. The mean bias from 6a is difficult to characterize theoretically and is characterized during validation, and assumed to be primarily from the first term (e.g. spectroscopy). Equation 6b represents the propagation of these same error types into a varying error. Although Eq. 6b has overall zero bias, it can produce regional and temporal biases, e.g. as seen in Connor et al. (2016), where these biases approach zero over long enough spatial or temporal scales. The error covariances all represent fractional errors, in log(VMR). The error in ppb is approximately the fractional error times the methane value in ppb."

Reviewer 1, 5): "3.2 Approach for Comparing AIRS measurements to aircraft profiles", page 9, lines 259-260 It should be more explained why "red" (mean obs. errors) minus "green" yields the cross-state error.

Response: We removed the statement in question. It now reads, "Figure 3 shows the predicted errors for the AIRS partial column XCH4 VMR within the pressure levels measured by the aircraft. The measurement error (light green) is 18 ppb (from the last term of Eq. 7b) , and the total error for a single observation (including smoothing error) is 41 ppb. A component of the total error, the cross-state error, is estimated as 21 ppb (from Eq. 7b)."

Reviewer 1 6) "3.3 Estimating validation error due to aircraft not measuring the stratosphere", page 9 I agree that the assumption in the stratosphere could significantly contribute to the differences between AIRS and aircraft data, but the amount of the validation error attributed to the stratosphere where aircraft cannot make observations should depend on how accurate each of the models (a priori, LMDz, and GC) can define the tropopause height; this may be a reason why we see relatively larger variabilities in the differences between AIRS and aircraft (simulated) in northern mid-latitudes."

Response: We agree that the stratospheric error depends on the accuracy of the model used to extend the validation data. We estimated the error for the model that we used in our validation. Added statement on page 9 "This estimate depends on the accuracy of the model used to extend the aircraft profile during the validation process, and was estimated for the model that we used in validation."

Reviewer 1 7) Overall, it is better to describe a bit more clearly which of errors the authors think is a systematic or random one. The authors have already referred to which is which for each of the error components in several parts of the text, but there are too many error values and they sometimes resemble another one; it is an option to add a table to summarize the characteristics of each of the error components.

Response: Added statement after Eq. 6b to indicate that the overall bias primarly results from the first term in Eq. 6a. However, the split of errors into "random" and "systematic" is not straightforward. Added a statement after Eq. 6b, "Although Eq. 6b has overall zero bias, it can produce regional and temporal biases, e.g. as seen in

Connor et al. (2016), where these biases approach zero over long enough spatial or temporal scales."

Minor comments from reviewer 1.

1) Figure 1 It is easy to see if the international dateline is centered.

Response: Referee suggests switching view on Figure 1. This was updated, as well as the colors and symbols used, as requested elsewhere.

2) page 5, line 137 "... such as check on the " "2, residual signals, ...", a symbol before "2" is missing.

Response: Fixed. "We use similar quality flags as the TES retrievals such as checks on the radiance residual, ..."

3) page 6, line 165 The symbols in the text do not correspond to those in the equations.

Response: Fixed.

4) Figure 2 The authors should explain the color shading in more details; which pressure layers do colors indicate?

Response: The levels are listed in the figure caption with several of the pressures shown on the plot itself.

5) page 8, line 251 Which is correct, A_cn in the text or A_cs in Equation (6)? Or A_cs and A_cs are used as the same meaning?

Response: The reviewer helpfully pointed out inconsistent notation. We did a switch from calling the non-measured part of the atmosphere "n" to "s" during the paper formation, so all the Acn should be Acs. Updated the text. Thank you.

6) Figure 3 The authors should give more explanations in the caption using the terms in the equations in the text.

Response: We now show the equation for the "smoothing error" in Eq. 5. Label Eq.

7 as the "observation error". The text for Figure 3 now reads, "The total error shown is the smoothing error (Eq. 5) plus the observation error (Eq. 7b). The measurement error is the last term of Eq. 7b, and the only fully random error."

7) "Figures 5 and 6 it may be better to replace the figure numbers".

Response: I switched these two figures (was a clearer note in embedded comments in paper)

8) page 10, lines 294-295 Why did the author choose HIPPO-4 observations to estimate bias correction values?

Response: Added a sentence to describe why HIPPO-4 was chosen, "HIPPO-4 was selected as it covers a wide range of latitudes and so that the bias correction can be set and tested with two independent datasets."

9) page 10, lines 295-296 Equation 5 is split into two: Eq. 5a and Eq. 5b. Are they combined?

Response: Yes, Eq. 5 was split into 5a and 5b, but later referred to as "Equation 5". The text was updated here and one other place to refer to Eq. 5b.

10) Figures 6 and 7 The bias values shown in the figures do not correspond to the values in the text. The authors should explain the values in the captions of the figures.

Response: Thank you for noticing that. New text is added for Fig. 5 and 7 (Fig 5 & 6 were swapped based on the previous reviewer comments). The values in the paper were outdated, and updated. Here is the updated text describing the biases shown in Fig 7, "Figure 7 shows the same comparisons as Fig. 5 after bias correction (described in Section 3.4). The mean bias is 1 ppb, and the RMS difference is 24 ppb. The overall land bias is 12 ppb, and the overall ocean bias is -2 ppb. The bias calculated in Fig. 7 is weighs every point equally. Table A.1 shows a slightly different result for these biases, where the bias is calculated by campaign, then averaged over all campaigns. In Table A.1 the partial column XCH4 VMR within the pressure levels measured by the aircraft

has a bias of 16 ppb for land, and -2 ppb for ocean."

11) page 12, line 350 Where does "24" come from?

Response: This comes from the single observation RMS, shown in Fig. 7. The text is updated to "Figure 8 shows the predicted error, assuming that the error is random, which is calculated by dividing the single observation error (24 ppb RMS shown in Fig. 7) by the square root of the number of observations that are averaged. The mean predicted error for the averaged data, assuming random errors, is 6 ppb. The actual standard deviation between the averaged AIRS and HIPPO or ATom data is $\sim$17 ppb, which is much larger and indicates that the errors within 1 day and 50 km are correlated."

12) page 12, line 363 It is better to add an explanation of 5.4 ppb (growth rate per year calculated at this site?).

Response: Added text "The growth rate of 5.4 ppb/year is the mean increase during the AIRS record time period (2002-2019) estimated from the NOAA Global Monitoring Laboratory global surface measurements (https://esrl.noaa.gov/gmd/ccgg/trends_ch4/). Since we are converting matched pairs of aircraft and AIRS to 2012, the differences between these matched pairs is unaffected by the accuracy of the conversion to 2012."

13) page 12, lines 378-380 Does this sentence mean that there are some correlations among each of the differences between collocated AIRS and aircraft pairs and the correlations cannot be compensated when taking averages on a daily basis?

Rsponse: Yes. Updated the wording to say this more clearly, "The standard deviation for daily observations is 15.2 ppb. This can be compared to the predicted error assuming randomness of 5.9 ppb (23 ppb divided by the square root of the number of observations averaged) Since 15.2 ppb is much larger than 5.9 ppb, this indicates that there are correlated (non-random) errors on the order of 15 ppb when averaging nearby observations within 1 day."

Other changes:

Author institution updated for Edward J. Dlugokencky to "National Oceanic and Atmospheric Administration, Global Monitoring Laboratory, Boulder, CO, USA"

NOAA ESRL aircraft changed to "NOAA GML aircraft network" due to an updated name for this program.

Thank you to both reviewers for their helpful comments. We have responded to all reviewer comments.

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