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Comment

Interactive comment on “Aircraft validation of Aura Tropospheric Emission Spectrometer retrievals of HDO and H₂O” by R. L. Herman et al.

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Authors' response to anonymous referee #2 on “Aircraft validation of Aura Tropospheric Emission Spectrometer retrievals of HDO and H₂O” by R. L. Herman et al., AMTD, 7, 3801–33, 2014.

We would like to thank the reviewer #2 for detailed review and helpful comments on our manuscript.

Reviewer's general comments: “The paper uses the comparatively precise and accurate measurements of H₂O and HDO taken through several aircraft campaigns over Alaska to validate profiles of the same entities produced from EOS AURA TES nadir measurements.

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The paper is well written and its scope fits well into AMT. It will be useful to users of TES HDO data as this comparison validates and enhances on the error budget of the retrieved data. However, in its current state, it seems a bit too much like a delta improvement to referenced papers; it should thus be improved by making it more self-contained, especially with respect to the in situ comparison and the bias correction, to reduce the need to reference preceding papers to understand this one.”

Response: We have addressed all of the reviewer’s specific comments and technical corrections below. New text added in response makes this paper more self-contained (see also the pdf supplement to our response to reviewer #1).

SPECIFIC COMMENTS: 1. Reviewer: “page 3809, line 15: The paper states that the in situ data are interpolated onto a very fine grid. This seems strange, as, first, the in situ data should be given on a fine grid to start with and, second, Fig. 3 seems to indicate that only data on a very coarse grid is employed.”

Response: Thank you for pointing this out. The old text was incorrect, we did not interpolate onto a very fine grid. Instead, the aircraft data were interpolated to the TES forward model levels (see specific comment #2 for further details). We have modified the text as follows:

New text on page 3809, line 15: “For comparison with TES, the in situ HDO and H₂O profiles are extended to cover the full range of TES levels. In the boundary layer, from the surface up to the lowest altitude aircraft data, we assume constant values of HDO and H₂O set equal to the first aircraft measurement. In the range of aircraft data (boundary layer to 5 km ceiling), the aircraft in situ HDO and H₂O data are interpolated to the levels of the TES forward model. It is quite likely that fine scale features are not captured this way, but these features are negligible at the TES vertical resolution (see averaging kernel in Fig. 3c). In the top layer, above the aircraft maximum altitude, the profile is extrapolated using a scaled a priori profile (see Sect. 4.4 for details).”

2. Reviewer: “The references given, give quite a lot of detail with respect to mapping

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matrices between grids of different resolutions, but the Fig. 3 looks a lot as if “just” the value of the insitu profile at the appropriate level was chosen/sampled. The paper should be improved to make the employed method clear, ideally without having to cross-reference a chain of previous papers. In case the in situ data was actually only sampled on a coarse grid, the effect of that drastic downsampling should be estimated, e.g. by the formula $x_{\text{insitu/AK}} = (I-A) x_a + G \cdot F'_{\text{insitu_grid}} x_{\text{insitu}}$ where F' is a Jacobian of the forward model with respect to the original in situ grid.”

Response: We agree with the reviewer that this description should be clearer. The aircraft data were interpolated to the TES forward model levels using the `idl` function `INTERPOL`. As mentioned above in point 1, we have modified the text on page 3809, line 15:

New text: “For comparison with TES, the in situ HDO and H₂O profiles are extended to cover the full range of TES levels. In the boundary layer, from the surface up to the lowest altitude aircraft data, we assume constant values of HDO and H₂O set equal to the first aircraft measurement. In the range of aircraft data (boundary layer to 5 km ceiling), the aircraft in situ HDO and H₂O data are interpolated to the levels of the TES forward model. It is quite likely that fine scale features are not captured this way, but these features are negligible at the TES vertical resolution (see averaging kernel in Fig. 3c). In the top layer, above the aircraft maximum altitude, the profile is extrapolated using a scaled a priori profile (see Sect. 4.4 for details).”

To support this statement, Figure 3c shows that the HDO averaging kernels are very broad compared to the fine scale features of the in situ measurements. As a sensitivity test, we fitted the in situ data three different ways (50-point, 100-point, and 200-point smoothing) to represent different resolutions. When the TES operator (Averaging kernel) is applied, the results differ by at most ± 2 per mil, which is negligible compared to other sources of error. H₂O varies more than HDO/H₂O, but that is beyond the scope of this paper on HDO/H₂O validation.

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3. Reviewer: “page 3812, Sect. 4.3 / Fig. 4: This section describes how a new bias correction is derived. It is confusing that Fig.4 shows already the bias corrected values (this is not obviously given in the caption, but can be derived from the text), as it shows the bias of the bias corrected values. It might be helpful to visualise this correction by also plotting the bias-uncorrected values together with the linear fit used for correction as a second plot to the left.”

Response: We thank the reviewer for this suggestion, and have revised with the linear bias correction (new Figure 4a), uncorrected comparison (new Figure 4b), and bias-corrected values (new Figure 4c).

4. Reviewer: “Further, why was a linear relation chosen?”

Response: TES Version 4 data used a constant bias correction at all altitudes, but it became apparent from our work that the Version 5 bias changes with altitude. We selected a linear relation for the fit because it was the simplest function that varies smoothly with pressure. The following text has been added to page 3813, line 3:

New text on page 3813, line 3: “A linear relation was chosen because it is a simple function that varies smoothly with pressure.”

5. Reviewer: “page 3812, Section 4.3: It should be explicitly discussed, why the bias correction derived over a rather specific local region and time of year can be used for the globally derived HDO/H₂O ratios.”

Response: This is an excellent point, also raised by the other reviewer. To test our bias correction, we have reanalyzed TES – in situ δD comparisons in two subtropical locations, Hawaii and the Mediterranean Sea. We compared TES version 5 observations with the Hawaii in-situ data described by Worden et al. (2011) and airborne Picarro measurements over the Mediterranean from the European HyMeX field mission (H. Sodemann, personal communication, 2014). Both sets of comparisons agree to within the TES estimated error, so we have confidence that the bias correction can be used

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globally. The Hawaii analysis is beyond the scope of this paper because further explanation is required for how the surface data are analyzed. Our European collaborators have requested that the HyMeX comparison not be shown in this paper (due to complications with the airborne instrument). As a result, we have added the following brief text to the end of Section 4.3:

New Text on page 3813, line 5: “To test whether this bias correction can be applied globally, TES observations have been compared to coincident in situ measurements from Mauna Loa, Hawaii, (Worden et al., 2011) and the Mediterranean Sea (H. Sode-
mann, personal communication, 2014). Once the TES operator is applied to the in situ data (Eq. 1), the TES and in situ δD profiles agree to within the TES estimated error.”

MINOR/TECHNICAL CORRECTIONS: 1. Reviewer: “page 3806, line 4: The employed spectral range is given to be the entire range from 1170 to 1330 cm^{-1} , but the referenced paper states it to be the range depicted in its Fig. 1, which goes only to 1320 cm^{-1} . Also, the referenced paper mentions that some regions are excluded, making it at most “almost the entire range”.”

Response: We thank the reviewer for this suggestion. We have replaced ‘The entire spectral range between 1170 and 1330 cm^{-1} ’ with:

New text on page 3806, line 4: “Nearly the entire spectral range between 1190 and 1317 cm^{-1} , with some small regions excluded”

2. Reviewer: “page 3806, line 24: Is the data (log-)linearly interpolated?”

Response: The water mixing ratios from GMAO GEOS-5 are linearly interpolated to the TES location and levels in log(pressure). We have replaced the sentence on page 3806, line 24, with:

New text on page 3086, line 24: “The GMAO GEOS-5.2 water mixing ratios are linearly interpolated to the latitudes, longitudes, and log(pressure) levels of TES retrievals to generate the a priori profiles.”

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3. Reviewer: “page 3811, line 14: It might be beneficial to either constantly use geometric altitudes or pressure levels, but to not switch in between them.”

Response: We will change the altitude units from hPa pressure to meters geometric altitude to be consistent with the figures, which are all shown in meters altitude. We will add new columns in Tables 2 and 3 for altitude. Here is the new text through the paper:

New text on page 3811, lines 6-16: “The standard deviation of δD has one peak at approximately 2000 m altitude (826 hPa pressure level) and another broad peak at 5000 to 7000 m altitude (511 to 422 hPa pressure levels) because the peak variability also corresponds to the levels with peak TES sensitivity to HDO/H₂O. The overall mean δD and standard deviation of δD are shown in bold red lines in Figure 2, and also listed in Table 3. Scan-to-scan variability in these TES retrievals is characterized by the standard deviation of δD ($1-\sigma$), which is $\pm 34.1\%$ in the boundary layer (averaging the data from 900 m and 1700 m altitudes), and $\pm 26.5\%$ in the free troposphere (averaging data between 2500 m and 7700 m altitudes). This analysis excludes the surface level, and altitudes above 8000 m, due to decreased TES sensitivity to HDO at those levels (i.e., more influenced by the prior).”

Also New text on page 3813, lines 3-5: “This corresponds to a typical TES bias of +98% in the boundary layer (average for 900 m and 1700 m altitudes), and +37% in the free troposphere (average for 2500 m to 7700 m altitude range).

Also New text on page 3815, lines 14-17: “In the boundary layer, up to 1700 m altitude, the empirical error is 0.029 (corresponding to $\pm 26\%$ error in δD) and the observation error is 0.017 (corresponding to $\pm 16\%$ error in δD). In the lower troposphere, 2500 m to 3300 m altitude, the errors have local minima.”

Also New text on page 3816, lines 16-19: “From analysis of twenty seven TES transects over the Alaskan boreal forest, the scan-to-scan variability of δD is $\pm 34.1\%$ in the boundary layer (averaging the data from 900 m to 1700 m altitude), and $\pm 26.5\%$ in the

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free troposphere (2500 m to 7700 m altitude).”

Also New text on page 3816, lines 27-29: “From the HDO/H₂O observation error, the TES estimated error is $\pm 16\%$ in the boundary layer (up to 1700 m), decreasing to $\pm 10.5\%$ at 2500 m to 3300 m, and then increasing at higher altitudes due to uncertainty in the true profile above the aircraft ceiling.”

Also New text on Table 4 caption: “Table 4. Error Budget for Aura TES V005 δD . Error terms are shown for both the boundary layer (up to 1700 m) and the free troposphere from 2500 m altitude up to the aircraft ceiling of 5000 m.”

4. Reviewers: “page 3812, line 16: Actually, Worden11 gives Worden07 as source for this equation; even though the equation cannot be easily identified in the older paper.”

Response: We thank the reviewer for pointing this out. Our equation 2 comes from Worden (2011) equation 1, which is derived from the Supplementary Information (equation 2.8) of Worden (2007). We have changed the text on page 3812, lines 15-16 to:

New text on page 3812, lines 15-16: “To properly account for the sensitivity of the TES retrieval, Worden et al. (2011) reports a bias correction (his Eq. 1) based on Eq. 2.8 of the Supplementary Information of J. Worden et al. (2007):”

5. Reviewer: “page 3811, lines 20f.: In this section, it is specified how the insitu profile is extended towards the ground, but not how it is extended above the aircraft ceiling. At least a reference to Sect. 4.4 should be given here.”

Response: The reviewer has a good suggestion. We will add a text description on pages 3809 and 3811 and refer to Section 4.4:

New sentence on page 3809, line 15f: “In the top layer, above the aircraft maximum altitude, the profile is extrapolated using a scaled a priori profile (see Sect. 4.4 for details).” New sentence on page 3811, line 25: “Above the aircraft ceiling, a scaled prior is used to extend the in situ profile (see Section 4.4).”

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6. Reviewer: “page 3814, line 15: How is the prior profile for extending the measured profile defined? Is this the same tropical one used as a priori for the retrieval or a more fitting one for the time and place of the in situ measurements?”

Response: For clarification, we think the reviewer meant page 3813, line 15, instead of page 3814. The reviewer is correct that a more detailed description of the prior would help clarify this section. The unscaled prior profile is the same tropical one used as a priori for the retrieval (described on page 3806, lines 25-27). However, the scaled prior (described on page 3813, lines 15-19) is meant to be a more fitting one for the time and place of the in situ measurements (i.e. high latitude northern summer). The scaled prior is continuous with the highest-altitude aircraft δD measurements, decreasing with height as expected from Rayleigh fractionation. We have modified the text as follows: New Text, Page 3806, lines 25-27: “In the TES product files, a priori HDO is defined as the product of the local a priori H₂O profile (GMAO GEOS-5.2) and one tropical a priori profile of the HDO/H₂O isotopic ratio (Worden et al., 2006). This is an overestimate of the expected HDO/H₂O ratio at high northern latitudes because of fractionation effects (e.g. Craig, 1961; Dansgaard, 1964), as discussed further in Section 4.4.”

Revised text, page 3813, lines 15-20: “The prior HDO/H₂O profile is multiplied by a constant factor so that its value at the TES level nearest the aircraft ceiling matches the aircraft HDO/H₂O. The prior HDO/H₂O is multiplied by the same constant factor at levels from the aircraft ceiling up to the tropopause. An unscaled prior is used above the tropopause. A scaled prior is more realistic for summer observations over Alaska because it is expected from previous measurements that HDO/H₂O should gradually decrease with altitude due to isotopic fractionation in the Arctic troposphere.”

7. Reviewer: “page 3815, line 11: It is not clear how many profiles are contained in that match of 28 July. Further, it might be simpler to also plot and describe values of these errors in per mill.”

Response: Thank you for pointing this out. Nineteen TES-aircraft pairs of observations

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are contained in this figure, and we will modify the text as described below. We will add a plot with errors in per mil units.

New text on page 3815, line 11: “Figure 6 is a comparison between TES HDO/H₂O observation error (red dashed line) and empirical error (solid black line) for n equals 19 matched TES-aircraft pairs of observations.”

Interactive comment on Atmos. Meas. Tech. Discuss., 7, 3801, 2014.

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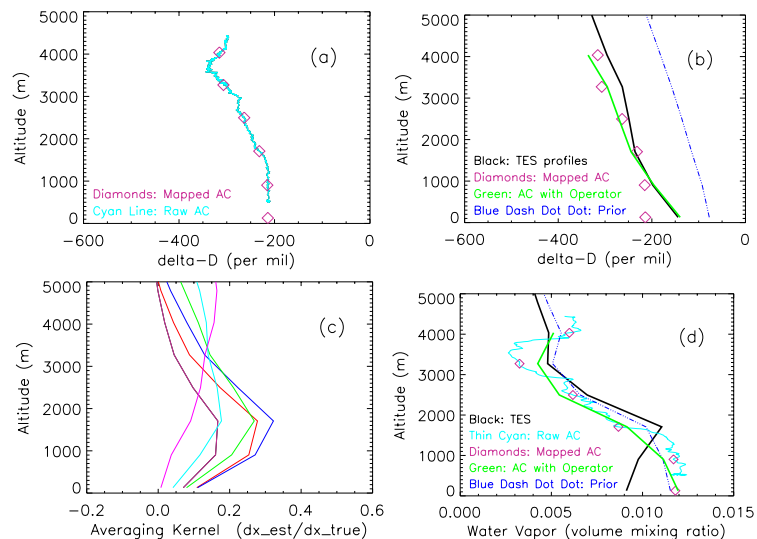


Fig. 3. Comparison of the δD tropospheric profile from the Alaskan interior boreal forest aircraft flight of 28 July 2012 with the coincident TES retrieval (run 15143, scan 12). **(a)** Raw aircraft ascent δD (cyan line) and aircraft values interpolated to TES levels (red diamonds); **(b)** δD profiles of the tropical prior (blue dash dot dot line), aircraft interpolated to TES levels (red diamonds), aircraft with TES operator (green line), and the TES retrieval (black line); **(c)** TES HDO averaging kernels for these lowest levels of the atmosphere; **(d)** H_2O profiles of the TES retrieval (black line), raw aircraft ascent data (cyan line), aircraft interpolated to TES levels (red diamonds), aircraft with TES operator (green line), and the H_2O prior from GMAO GEOS-5.2 (blue dash dot dot line).

Fig. 1. Author's figure 3.

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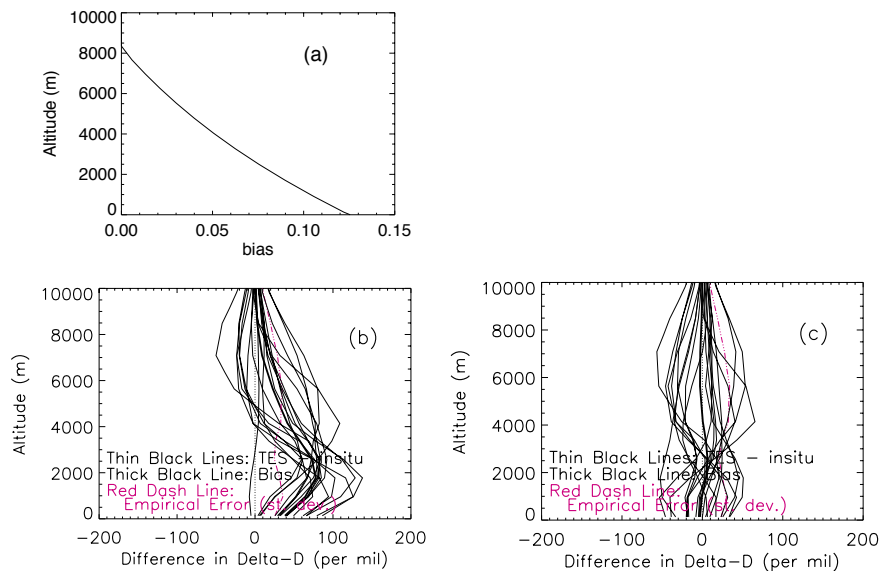



Fig. 4. (a) Bias: this is negative δ_{bias} from Eq. 3. (b) Uncorrected TES minus in situ (with TES operator). (c) Bias-corrected TES minus in situ (with TES operator).

Fig. 2. Author's figure 4.

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