John R. Worden[1], Susan S. Kulawik[2], Dejian Fu[1], Vivienne H. Payne[1], Alan E. Lipton[3], Igor Polonsky[3], Yuguang He[3], Karen Cady-Pereira[3], Jean-Luc Moncet[3], Robert L. Herman[1], Frederick W. Irion[1], and Kevin W. Bowman[1]

Deleted: Bill

1. Jet Propulsion Laboratory / California Institute for Technology, Pasadena, CA
2. Bay Area Environmental Research Institute, Mountain View CA, USA
3. Atmospheric Environmental Research, Lexington MA, USA

Characterization and Evaluation of AIRS-Based Estimates of the Deuterium Content of Water Vapor

Abstract: Single pixel, tropospheric retrievals of HDO and H_2O concentrations are retrieved from Atmospheric Infrared Sounder (AIRS) radiances using the optimal estimation algorithm developed for the Aura Tropospheric Emission Spectrometer (TES) project. We evaluate the error characteristics and vertical sensitivity of AIRS measurements corresponding to five days of TES data (or 5 global surveys) during the Northern Hemisphere summers between 2006 and 2010 (~600 co-located comparisons per day). We find that the retrieval characteristics of the AIRS deuterium content measurements have similar vertical resolution middle-troposphere as TES but with slightly less sensitivity in the lower-most troposphere, with a typical degrees-of-freedom (DOFS) in the tropics of 1.5 and approximately double the uncertainty. The calculated measurement uncertainty is ~30 per mil (parts per thousand relative to the deuterium composition of ocean water) for a tropospheric average between 750 and 350 hPa, the altitude region where AIRS is most sensitive. Comparison with the TES data also indicate that the uncertainty of a single target AIRS HDO/H_2O measurement is ~30 per mil. Comparison of AIRS and TES data between 30 degrees South and 50 degrees North indicate that the AIRS data is biased low by ~-2.6 per mil with a latitudinal variation of ~7.8 per mil. This latitudinal variation is consistent with the accuracy of TES data as compared to in situ measurements, suggesting that both AIRS and TES have similar accuracy.

Deleted: These retrievals are evaluated against co-located TES observations taken between 2006 through 2010.

Deleted: and uncertainty in the

Deleted: suggest

Deleted: calculated and actual

Deleted: suggest

Deleted: 8

Introduction:

Measurements of the isotopic composition of water can help identify the source of the water and provide knowledge about its condensation and evaporation history (e.g. Galewsky *et al*. and refs therein). Through most of the twentieth century, most isotopic measurements of water have been of precipitation (e.g. Craig, 1961). Near global measurements of the isotopic composition of water vapor became possible with the advent of spectroscopic techniques applied to in situ measurements (e.g., Noone *et al*., 2011) using lasers and for passive ground based and satellite measurements (e.g. Worden *et al*., 2006; Frankenberg *et al*. 2009; Schneider *et al*. 2012; Lacour *et al*. 2012). These data have in turn been used to evaluate the role of convection, large scale dynamics, and evapotranspiration on the tropical water cycle (e.g. Worden *et al*. 2007; Frankenberg *et al*. 2009; Wright *et al*. 2017) tropical convection (e.g. Lacour 2018 and refs therein) and the role of plants on global evapotranspiration (Good *et al*. 2015).

In this paper we demonstrate a retrieval algorithm, based upon the Aura TES optimal estimation retrieval algorithm (e.g. Worden *et al*. 2012) that can provide robustly characterized measurements of the deuterium content of water vapor (HDO and H_2O) from the AIRS measurements. Our goal is to create a multi-decadal Earth Science Data Record (ESDR) using the AIRS and TES data; the TES global record spans ~6 years (2005-2010) and the AIRS data span 17+ years starting in 2002. This ESDR could potentially be used for evaluating the changing water cycle (e.g. Bailey *et al*., 2017) and its coupling to the carbon cycle (e.g. Zhou *et al*., 2014; Wright *et al*., 2017).

We first characterize the vertical resolution and uncertainties for estimates of HDO and H_2O, and their ratio, using AIRS radiance observations corresponding to boreal summertime TES global survey's between 2006 through 2010, which is the time period when TES observations sample the (near) global atmosphere and the calibration approach for TES measurements remained the same. We make only these comparisons due to current processing limitations but expect additional overlap between TES and AIRS data sets in the coming years. We then compare the AIRS and TES data to evaluate the calculated uncertainties of the AIRS data.

1) Description of AIRS and TES instruments

The AIRS instrument is a nadir-viewing, scanning infrared spectrometer (Aumann *et al*. 2003; Pagano *et al*., 2003; Irion *et al*. 2018; DeSouza-Machado *et al*. 2018) that is onboard the

Formatted: Font: Times, Bold

Formatted: Font: Times

Formatted: Font: (Default) Times

Formatted: Normal, Indent: First line: 0.5", Space Before: 0 pt, After: 0 pt, Line spacing: 1.5 lines, No bullets or numbering

Formatted: Font: (Default) Times

Formatted: Font: (Default) Times

Deleted: and TES

Deleted: n

Deleted: Earth Science Data Record (

Deleted:)

Deleted: , as

Deleted: Worden *et al*. 2007a; Frankenberg *et al*. 2010; Risi *et al*. 2012; Frankenberg *et al*. 2013; Galewsky *et al*., 2016;

Deleted: ; Wright *et al*., 2017

Deleted: ; Wright *et al*. 2017

Deleted: The algorithm we use also jointly retrieves methane from the AIRS radiances (e.g. Xiong *et al*. 2008, 2013) and we will use these methane retrievals for the purpose of creating a joint AIRS / TES record of CH_4 and for quantifying lower-tropospheric methane (Worden *et al*., 2015) by combining these data with total column methane measurements (Worden *et al*., 2013 Worden *et al*., 2017). However, the evaluation and validation of these methane retrievals will be discussed in a subsequent paper.

Deleted: H_2O

Deleted: and quantify

Deleted: A follow-on paper will compare these AIRS data to aircraft data taken during the NASA ORACLES (ObseRvations of Aerosols above CLouds and their intEractionS) campaign.

Formatted: Font: Not Bold

Deleted: 2)

Formatted: Font: Times, Bold

Formatted: List Paragraph, Numbered + Level: 1 + Numbering Style: 1, 2, 3, … + Start at: 1 + Alignment: Left + Aligned at: 0.25" + Indent at: 0.5"

Deleted: 3

NASA Aqua satellite and was launched in 2002. AIRS measures the thermal radiance between approximately 3-12 microns with a resolving power of approximately 1200. For the 8 micron spectral range used for the HDO/H_2O retrievals, the spectral resolution is ~1 cm^{-1} with a gridding of ~0.5 cm^{-1}; the signal-to-noise (SNR) ranges from ~400 to ~1000 over the 8 micron region for a typical tropical scene. A single footprint has a diameter of ~15 km in the nadir; with the ~1650 km swath, the AIRS instrument can measure nearly the whole globe in a single day. The Aqua satellite is part of the "A-Train" that consists of multiple satellites, including TES, in a sun-synchronous orbit at 705 km with an approximately 1:30 pm equator crossing-time.

The Aura TES instrument is a Fourier Transform Spectrometer that originally was designed to measure the thermal infrared (IR) radiances both in the limb and nadir viewing in order to obtain vertically resolved trace gas profiles of ozone, CO, CH_4, HDO and H_2O, and several ozone pre-cursors such as ammonia, methanol, and PAN (e.g. Beer *et al.*, 2001; Worden *et al.*, 2004; Worden *et al*. 2006; Luo *et al.*, 2007; Beer *et al*. 2008; Worden *et al.*, 2012; Payne *et al*. 2014). Several of these trace gases, such as CO, CH_4, and ammonia have also been quantified using AIRS radiances (e.g. McMillan *et al.*, 2005; Xiong *et al*. 2008; Warner *et al.*, 2016). In comparison to the AIRS instrument, TES has a spectral resolution of ~0.12 cm^{-1} (apodized) with a spectral gridding of 0.06 cm^{-1}. The SNR is ~300 in the 8 microns spectral region. The Aura TES instrument, after the summer of 2005, observes one nadir scene every 100 km along the orbit path. The effective length of the record is approximately five years, between September 2005 through November 2009, after which instrument degradation problems resulted in interrupts and a decrease in sampling. The AIRS instrument has nearly one thousand times the sampling of TES and near continuous operation between 2002 through the present and therefore can be used to construct several composition based ESDR's.

Deleted: The A-Train also consists of

Deleted: t

Deleted: which

Deleted: es

Deleted: ,

Deleted: ;

Deleted: Earth System Data Records (

Deleted:)

3) Description of the Radiative Transfer Forward Model

The radiative transfer forward model used for this work is the Optimal Spectral Sampling (OSS) fast radiative transfer model (RTM) (Moncet et al., 2015; Moncet et al., 2008). The OSS approach is integrated in the operational Cross-Track Infrared Sounder (CrIS, Han et al. 2013) processing system (Divarkala et al., 2014) and has also been utilized for trace gas retrievals from CrIS (e.g. Shephard and Cady-Pereira, 2015). OSS uses a series of approximations tailored to a

Deleted: Moncet et al., 2005;

Deleted: [

Deleted:]

specific frequency range and spectral resolution to increase the radiative transfer calculation performance by approximately a factor of 20-100 relative to a line-by-line calculation (http://rtweb.aer.com). OSS can be trained to user-defined accuracy relative to the line-by-line model used for training. Here, the training threshold was set to 20 % of the AIRS noise level. The line-by-line model used as a reference in the training and to build the absorption coefficient look-up tables (LUTs) used by the fast RTM is the Line-By-Line Radiative Transfer Model (LBLRTM) (Clough et al., 2005; Alvarado et al., 2013). The OSS version used in this work is based on LBLRTM v12.4, using the TES_v2.0 spectroscopic line parameter database. The TES_v2.0 line parameter database follows the HITRAN 2012 compilation (Rothman et al., 2013]), with the following exceptions:

- H_2O positions and intensities are taken from the aer_v_3.4 line parameter database (http://rtweb.aer.com), closely following the measured and calculated values published in Coudert et al. (2008).
- CH_4 includes first order line mixing coefficients (as supplied in the aer_v_3.4 line parameter database). These were calculated using the approach of Tran et al. (2006).
- CO_2 line parameters are from the database of Lamouroux et al. (2015). This database takes most of its line positions, intensities, and lower state energies from the HITRAN 2012 database, but the values for air-broadening half-widths and their temperature dependences are adjusted from the HITRAN 2012 values to be consistent throughout the bands, and the air-induced pressure shifts (not given for a majority of transitions in HITRAN 2012) were added. The TES_v2.0 database includes first order line mixing coefficients (as supplied in the aer_v_3.4.1 line parameter database), calculated using the software of Lamouroux et al. (2015).

Further information on the AER line parameter databases can be found at http://rtweb.aer.com. OSS is adapted for use with AIRS radiances using the version 4 AIRS spectral response function (SRF) (Strow et al., 2003) that is interpolated to a uniform grid of 0.004 cm^{-1} centered on the channel center frequencies. The OSS radiative transfer code provides speedup of 20-100x over the original TES operational radiation transfer model (Clough *et al*., 2006).

4) Description of the Retrieval Approach

Deleted: [

Deleted: [

Deleted:]

Deleted: [

Deleted:]

Deleted: [

Deleted:]

Deleted: pressure shifts

Deleted: [

Deleted:]

Deleted: a version of the v4

Deleted: [

Deleted:]

The optimal estimation algorithm used in this analysis for quantifying CH_4, HDO, H_2O, temperature, cloud properties, and emissivity is extensively discussed in Worden et al. (2004), Bowman et al. (2006), and Worden et al (2012). We therefore refer the reader to those papers for a description of the retrieval algorithm, with a suggestion that they start with the Worden *et al*. (2012) paper; however, we will briefly summarize the retrieval approach here. This retrieval algorithm, now called the MUlti-SpEctra, MUlti-SpEcies, MUlti-Sensors (MUSES) algorithm (Worden et al., 2007b; Fu et al., 2013, 2016, 2018; Luo et al., 2013; Worden et al., 2013), can use radiances from multiple instruments including TES, CrIS, OMI, OMPS, TROPOMI, and MLS to quantify geophysical observables that affect the corresponding radiance.

For the AIRS retrievals discussed here, we simultaneously estimate not just CH_4, CO, HDO, and H_2O but also temperature (surface and atmosphere), emissivity (if over land), and a spectrally varying gray body cloud (e.g. Kulawik *et al*., 2006, Eldering *et al*., 2008). As in Worden *et al*. (2006) and Worden *et al*. (2012) the constraint matrix used to regularize the HDO and H_2O components of the retrieval includes off-diagonal components that reflect *a priori* knowledge about the variability of HDO with respect to H_2O in order to ensure that retrieval of the ratio of HDO to H_2O is optimized, as opposed to either HDO or H_2O alone. The prior information used for this covariance is derived from monthly climatologies using the NCAR Global Climate Model as discussed in Worden *et al*. (2006). The *a priori* profile used for the HDO/H_2O ratio is set to be constant over the whole globe, and represents the mean tropical *a priori* profile from the NCAR model. However, the H_2O *a priori* profile is allowed to vary by latitude and is based on re-analysis (Worden *et al*. 2006); therefore the HDO profile is the mean tropical profile of the HDO/H_2O ratio from the NCAR model multiplied by the H_2O *a priori* profile.

We use single pixel radiances that have not been transformed through "cloud clearing" in order to preserve the original, well characterized radiance noise characteristics for use in our estimates (Irion *et al*. 2018; DeSouza-Machado *et al*. 2018) and because we find that single-pixel AIRS radiances have sufficient information about cloud pressure and optical depth to be retrieved jointly with the trace gases, as demonstrated empirically through validation of these AIRS-based composition retrievals with TES retrievals (e.g. Figures 1-4). We assume the noise in any given pixel is uncorrelated with those from adjacent pixels. However, these correlations

Deleted: ,

Moved (insertion) [1]

Deleted: and

Deleted: and characterize

Deleted: appropriate for

Deleted: Briefly, w

Deleted: e

Moved up [1]: This retrieval algorithm, now called the MUlti-SpEctra, MUlti-SpEcies, MUlti-Sensors (MUSES) algorithm (Worden et al., 2007b; Fu et al., 2013, 2016, 2018; Luo et al., 2013; Worden et al., 2013), can use radiances from multiple instruments including TES, CrIS, OMI, OMPS, TROPOMI, and MLS to quantify and characterize geophysical observables appropriate for the corresponding radiance.

are known to exist (e.g. Pagano *et al*. 2008) and the impact of ignoring them is that our calculated uncertainties will be larger than expected and therefore our noise related uncertainty should be considered a conservative estimate.

A primary difference between the retrieval approach shown in this paper versus the TES methane and HDO retrievals (Worden *et al*., 2012) and those from previous efforts using AIRS radiances (e.g. Xiong *et al*., 2008) is that we retrieve these trace gas profiles using the AIRS radiances from ~8 and ~12 microns instead of radiances from the 8 micron region alone in order to provide a stronger constraint on atmospheric temperature and hence reduce uncertainty from knowledge of temperature on the HDO and H_2O retrieval. The 8 micron region used (~1217 to 1315 cm^{-1}) for these retrievals has the most sensitivity to HDO and H_2O whereas the 12 micron band (~650 to 900 cm^{-1}) is primarily sensitive to temperature and H_2O.   All channels are used within this spectra unless flagged as poor during calibration.

5) Characterization of HDO/H_2O profiles

While H_2O is quantified using radiances from both the 12 micron and 8 micron spectral regions, the primary absorption lines used here to quantify HDO are in the 8 micron region. There are other HDO (and H_2O) lines available to use from the AIRS radiance but for now we only use the 8 micron region to ensure consistency between AIRS and TES data. Figure 1 shows the 8 micron radiance (top panel) and the Jacobian, or sensitivity of the radiance to variations in the (log) H_2O and (log) HDO respectively (middle and bottom panels). These Jacobians are normalized by the instrument noise. For example, a value of 1 means that it would take a 100% change in the corresponding species to distinguish between two similar radiances (everything about the observed scene and radiance is the same except for the species of interest) above the noise level. A value of ~-50 therefore means that only a 2% variation is required (or 1/50).

Figure 2 shows the averaging kernel matrix for the HDO component of the joint retrieval. The averaging kernel describes the response of the estimate, or log(HDO), relative to variations in the true state; consequently it can also be used to evaluate the vertical resolution and sensitivity of the estimate. For example, if HDO varies by 100% at 908 hPa, then the AIRS estimate would be able to observe about 30% of the variability because the averaging kernel is approximately 0.3 at that level. The averaging kernel at 908 hPa also depends on the deuterium

Deleted:

Deleted: s

Deleted: es

Deleted: to

Deleted: , with the caveat that the 9.6 micron ozone band is excluded

Deleted: Adding the AIRS measured radiance at 12 microns is critical for reducing uncertainties in the CH_4 estimate, which is discussed in a subsequent paper.

Deleted: ^{18}

Deleted: column

Deleted: Jacobians for

Deleted: with both the H_2O and HDO Jacobians indicating sufficient sensitivity above the noise level of the radiances to variations of better than 1% in H_2O and HDO, because most values are approximately -100 or better.

Deleted: partial derivative of the

Deleted: its

Deleted: the

Deleted: /H_2O

Deleted: ratio

Deleted: .

Deleted: In addition,

Deleted: t

content at several other pressure levels below and above indicating that the estimate at 908 hPa depends on the deuterium content variations at these other levels. Not shown are the dependencies of the (log) HDO estimate to those from the (log) H_2O estimate. These dependencies between the HDO averaging kernels and with the H_2O averaging kernels are accounted for when constructing the HDO/H_2O ratio; however a residual uncertainty called the "smoothing" error is imparted when comparing the HDO/H_2O ratio to independent data; this smoothing error is part of the error budget shown in Figure 3. As discussed in Worden *et al*. (2012) and Schneider *et al*. (2012), the sensitivity of the estimated HDO/H_2O ratio is limited by the sensitivity of the estimate to HDO. Users of these data should note that this ratio is typically used with that of H_2O in order to better evaluate their joint variation (HDO/H_2O, H_2O) against simple mixing and rainfall models (Noone *et al*. 2011). However, the sensitivity of the radiance to H_2O variations is much stronger than that for HDO, although the altitude region of the HDO sensitivity typically overlaps with the H_2O sensitivity. Schneider *et al*. (2012) discusses how to created HDO/H_2O, H_2O pairs to mitigate this component of the smoothing error when comparing these data against the simple models described in Noone *et al*. (2011). For comparison to more complex global climate models the user of these data also needs to apply the HDO and H_2O averaging kernels to the corresponding model fields (e.g. Risi *et al*., 2012).

Figure 3 (top panel) shows the tropospheric deuterium content (or HDO/H_2O ratio) derived from AIRS observations on July 1 2006. Despite the improved computational performance of the OSS radiative transfer calculation relative to the TES algorithm line-by-line calculation (Clough *et al*. 2005), the retrieval is still sufficiently expensive such that we can only process a sub-set of the AIRS retrievals. Considering the computational cost, for the purpose of constructing a record we currently only process AIRS retrievals from between 45 degrees South to 65 degrees North that coincide with the nearest TES observation but with an additional two observations within 100 km of the TES track over the continents; this ad hoc sampling strategy is based on experience with previous studies using the TES deuterium and methane measurements. The traditional notation for this quantity is called "delta-D" , or "δ-D" with units of "per mil" or parts per thousand relative to the Standard Mean Ocean Water (SMOW) deuterium content which is 3.11x10^{-4} molecules of HDO per molecule of H_2O. The observations shown represent the deuterium content for the pressures between 750 hPa and 350 hPa, where we find the AIRS and TES observations have maximal overlap in their vertical resolution.

Deleted: ,

Deleted: also

Deleted: .

Deleted:

Deleted: e

Deleted: units

Deleted: of

Deleted: are

The errors are calculated during the optimal estimation retrieval (Bowman *et al*. 2007; Worden *et al*. 2012) and depend on the expected noise of the AIRS radiances and the parameters that are co-retrieved with the AIRS HDO/H_2O ratio such as temperature, surface emissivity, clouds, and methane. As noted in Worden *et al*. (2012) these co-retrieved parameters affect both the precision and accuracy whereas the noise only affects the precision. The total error (middle panel) is given in units of per mil and ranges between 25 to 30 per mil. The DOFS, or trace of the averaging kernel, are shown in the bottom panel and indicate that many of the HDO/H_2O retrievals can resolve different parts of the troposphere, at least in the tropics, because (as demonstrated in Figure 2) the rows of the averaging kernels are separated between the boundary layer region (surface to ~750 hPa) and the free-troposphere (~600 to 300 hPa). However, these observations cannot completely resolve the total variability in these two regions of the atmosphere because the total DOFS is typically 1.5 or less and for the measurement to be able to resolve the variability (to within the calculated error) of the two regions there would need to be at least 2 DOFS.

Deleted: across the globe

Deleted: the

Deleted:

Deleted: approximately

6) Comparison of AIRS and TES HDO/H_2O retrievals

Figure 4 shows a comparison between overlapping AIRS and TES estimates of the HDO/H_2O ratio for June 1 2006. The AIRS and TES measurements effectively overlap in space and within a few seconds in time as the instruments are in the same orbit. However not all the comparisons shown in Figure 4 overlap as retrievals may be rejected due to poor quality. We therefore compare all data that are within 200 km in the free troposphere. We do not expect substantive error to occur due to spatial mismatch of 2 degrees or less because air parcels in the free-troposphere have length scales that are several hundred kilometers long (e.g. Worden *et al*. 2013). The average between approximately 750 hPa and 350 hPa are shown for when the DOFS are larger than one for this altitude region. There is a slight bias of -2.7 +/- 1.5 per mil between TES and AIRS as shown in the top panel. The calculated and actual (RMS difference between AIRS and TES) uncertainties are shown and are approximately 30 per mil, primarily driven by the uncertainty in the AIRS based estimates as the TES based estimates have an uncertainty of approximately 15 per mil. Figure 5 shows a direct comparison of the AIRS and TES data. The correlation is about 0.89 and the one-to-one line (solid line) overlaps this distribution. However the lowest values likely diverge from the one-to-one line, possibly because the vertical distribution in the sensitivity depends on the amount of HDO and hence we should expect differences between the TES and AIRS deuterium measurements for these lower-sensitivity retrievals.

Deleted: The calculated errors are calculated during optimal estimation retrieval (Bowman *et al*. 2007; Worden *et al*. 2012) and depend on the expected noise of the AIRS radiances and the parameters that are co-retrieved with the AIRS HDO/H_2O ratio such as temperature, surface emissivity, clouds, and methane. As noted in Worden *et al*. (2012) these co-retrieved parameters affect both the precision and accuracy whereas the noise only affects the precision.

A comparison of the AIRS and TES HDO/H_2O ratio for five single global surveys taken between 2006 and 2010 (one global survey per year during boreal summer) is shown in Table 1 and indicates that the overall bias varies between -2.7 to 3.7 per mil. Using all 5 TES global surveys that are summarized in Table 1 we can construct how AIRS and TES compare as a function of latitude as shown in Figure 6. Figure 6 is constructed by averaging the difference between TES and AIRS observations within 5 degree latitudinal bins. The mean bias across latitudes is ~-2.6 per mil. The error bars shown on the difference is the error on the mean, which is the Root-Mean-Square (RMS) of the differences divided by the square root of the number of co-located observations; as this error bar is a measure of precision for each latitude bin, this comparison demonstrates that there are variations in the comparison that are larger than the precision and are therefore related to systematic errors in either the TES data or AIRS data or both. Variations in these systematic errors can be seen in the latitudinal variability, which has an RMS variation of ~7.8 per mil for the different latitude bins but can vary by as much as ~-15 to ~+15 per mil in the tropics. Typically these variations are due to a combination of uncertainties in the spectroscopy along with temperature, water vapor, and surface properties; they may also be due to "smoothing error" which is related to how differences in the vertical resolution affect the tropospheric average of the deuterium content shown in these figures (e.g. Worden *et al.* 2004). This 7.8 per mil variation across latitudes is about the same as the reported accuracy of the Aura TES delta-d observations that are based on comparisons of TES data with surface and aircraft measurements (Worden *et al*. 2011; Herman *et al*. 2014). We therefore report the current accuracy of the AIRS data to be ~7.8 per mil. We expect future comparisons between these data and those from aircraft or revisions to the AIRS retrieval approach will modify this estimate of the accuracy.

Deleted: , for these comparisons

Deleted: 5

Deleted: 5

Deleted: The RMS of the

Deleted: is

Deleted: which is similar to the mean variations shown in Table 1 and also

Deleted: the

Deleted: take

Deleted: These comparisons therefore show that the AIRS estimates of the HDO/H_2O ratio are robust as the calculated and actual uncertainties are consistent with an accuracy comparable to observations from TES.

8) Conclusion

This paper describes the vertical resolution and error characteristics of retrievals of the deuterium content (or the HDO/H_2O ratio) of water vapor using AIRS radiances and then evaluates the consistency between AIRS and TES retrievals of HDO and H_2O. We find that the AIRS and TES deuterium content for the lower-troposphere (750 – 350 hPa) are consistent, or within their calculated uncertainties, for the 5 year period in which TES observations span the globe (2006-2010). We find the total uncertainty for a single AIRS observation is ~30 per mil with an accuracy of ~7.8 per mil. These uncertainties can be compared to the observed total variability, which can range from approximately -350 to -50 per mil over the whole globe, as observed by the Aura TES data (Worden *et al*. 2006) and shown in Figure 3 for AIRS data.

While only five days of comparisons are shown here for the purpose of evaluating the retrieval approach and error characteristics of these AIRS retrievals, we expect to produce a record of the AIRS-based deuterium content retrievals from the start of the mission (2002) through the present. Because of computational limitations, we expect to process data from 45 degrees South to 65 degrees North at approximately four times the sampling of the Aura TES measurements and with increased sampling (~3x) over the continental regions with the goal of increasing this sampling once the initial record is completed and as additional resources become available.

Acknowledgements

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Deleted: and

Deleted: H_2O

Deleted: 0

Deleted: 0

Deleted: .

Deleted: ¶
Table 1: Comparison between averaged TES and AIRS HDO/H_2O ratio (750-350 hPa). The units are in parts per thousand relative to Standard Mean Ocean Water. The last row shows the average and RMS for the mean differences in the far right column.¶
Date ... [1]

Moved down [2]: Table 1: Comparison between averaged TES and AIRS HDO/H_2O ratio (750-350 hPa). The units are in parts per thousand relative to Standard Mean Ocean Water. The last row shows the average and RMS for the mean differences in the far right column.¶
Date

References

Alvarado, M. J., Payne, V. H., Mlawer, E. J., Uymin, G., Shephard, M. W., Cady-Pereira, K. E., Delamere, J. S. and Moncet, J. L.: Performance of the Line-By-Line Radiative Transfer Model (LBLRTM) for temperature, water vapor, and trace gas retrievals: recent updates evaluated with IASI case studies, Atmospheric Chemistry and Physics, 13(14), 6687–6711, doi:10.5194/acp-13-6687-2013-supplement, 2013.

Aumann, H. H., Chahine, M. T., Gautier, C., Goldberg, M. D., Kalnay, E., McMillin, L. M., Revercomb, H., Rosenkranz, P. W., Smith, W. L., Staelin, D. H., Strow, L. L. and Susskind, J.: AIRS/AMSU/HSB on the aqua mission: design, science objectives, data products, and processing systems, IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, 41(2), 253–264, doi:10.1109/TGRS.2002.808356, 2003.

Bailey, A., Blossey, P. N., Noone, D., Nusbaumer, J. and Wood, R.: Detecting shifts in tropical moisture imbalances with satellite-derived isotope ratios in water vapor, Journal of Geophysical Research-Atmospheres, 122(11), 5763–5779, doi:10.1029/2010JD015197, 2017.

Beer, R., Glavich, T. A. and Rider, D. M.: Tropospheric emission spectrometer for the Earth Observing System's Aura satellite, Applied optics, 40(15), 2356–2367, 2001.

Beer, R., Shephard, M. W., Kulawik, S. S., Clough, S. A., Eldering, A., Bowman, K. W., Sander, S. P., Fisher, B. M., Payne, V. H., Luo, M., Osterman, G. B. and Worden, J. R.: First satellite observations of lower tropospheric ammonia and methanol, Geophysical Research Letters, 35(9), L09801, doi:10.1029/2008GL033642, 2008.

Bowman, K. W., Rodgers, C. D., Kulawik, S. S., Worden, J., Sarkissian, E., Osterman, G., Steck, T., Lou, M., Eldering, A. and Shephard, M.: Tropospheric emission spectrometer: Retrieval method and error analysis, IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, 44(5), 1297–1307, 2006.

Clough, S. A., M. W. Shephard, E. J. Mlawer, J. S. Delamere, M. J. Iacono, K. Cady-Pereira, S. Boukabara, and P. D. Brown: Atmospheric radiative transfer modeling: A summary of the AER codes. J. Quant. Spectroscopic. Radiative Transfer, 91, 233–244, doi: 10.1016/j.jqsrt.2004.05.058, 2005

Clough, S. A., Shephard, M. W., Worden, J., Brown, P. D., Worden, H. M., Luo, M., Rodgers, C. D., Rinsland, C. P., Goldman, A. and Brown, L.: Forward model and Jacobians for tropospheric emission spectrometer retrievals, IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, 44(5), 1308–1323, 2006.

Craig, H.: Isotopic variations in meteoric waters, Science, 133, 1702–1703, 1961.

Coudert, L, Wagner, G., Birk, M., Baranov, Y.I., Lafferty, W.J., Flaud, J-M.: The (H$_2$O)-O-16 molecule: Line position and line intensity analyses up to the second triad, Journal Molecular Spectroscopy., **251,** 339-357, 2008

Formatted: Font: Times

Deleted: Alvarado, M. J., V. H. Payne, E. J. Mlawer, G. Uymin, M. W. Shephard, K. E. Cady-Pereira, J. Delamere, and J-L. Moncet: Performance of the line-by-line radiative transfer model (LBLRTM) for temperature, water vapor, and trace gas retrievals: Recent updates evaluated with IASI case studies. Atmos. Chem. Phys. Discuss., 13, 79–144, doi: 10.5194/acpd-13-79-2013¶

Formatted: Font: Times

Formatted: Font: Times

Deleted: Beer, R., Shephard, M. W., Kulawik, S. S., Clough, S. A., Eldering, A., Bowman, K. W., Sander, S. P., Fisher, B. M., Payne, V. H., Luo, M., Osterman, G. B. and Worden, J. R.: First satellite observations of lower tropospheric ammonia and methanol, Geophys. Res. Lett, 35(9), L09801, doi:10.1029/2008GL033642, 2008.¶

Deleted: t

Deleted: .

Formatted: Font: Times

Field Code Changed

Deleted: .

Deleted: .

DeSouza-Machado, S., Strow, L. L., Tangborn, A., Huang, X., Chen, X., Liu, X., Wu, W. and Yang, Q.: Single-footprint retrievals for AIRS using a fast Two Slab cloud-representation model and the SARTA all-sky infrared radiative transfer algorithm, Atmospheric Measurement Techniques, 11(1), 529–550, doi:10.1029/2005GL023211, 2018.

Divakarla, M. G., and Coauthors: The CrIMSS EDR algorithm: Characterization, optimization, and validation. J. Geophysical Research-Atmospheres, 119, 4953–4977, doi: 10.1002/2013JD020438 (2014)

Eldering, A., Kulawik, S. S., Worden, J., Bowman, K. and Osterman, G.: Implementation of cloud retrievals for TES atmospheric retrievals: 2. Characterization of cloud top pressure and effective optical depth retrievals, Journal of Geophysical Research-Atmospheres, 113(D16), D16S37, doi:10.1029/2007JD008858, 2008.

Frankenberg, C., Yoshimura, K., Warneke, T., Aben, I., Butz, A., Deutscher, N., Griffith, D., Hase, F., Notholt, J., Schneider, M., Schrijver, H. and Rockmann, T.: Dynamic Processes Governing Lower-Tropospheric HDO/H2O Ratios as Observed from Space and Ground, Science, 325(5946), 1374–1377, doi:10.1126/science.1173791, 2009.

Frankenberg, C., Wunch, D., Toon, G., Risi, C., Scheepmaker, R., Lee, J.-E., Wennberg, P. and Worden, J.: Water vapor isotopologue retrievals from high-resolution GOSAT shortwave infrared spectra, Atmospheric Measurement Techniques, 6(2), 263–274, doi:10.5194/amt-6-263-2013, 2013.

Fu, D., Kulawik, S. S., Miyazaki, K., Bowman, K. W., Worden, J. R., Eldering, A., Livesey, N. J., Teixeira, J., Irion, F. W., Herman, R. L., Osterman, G. B., Liu, X., Levelt, P. F., Thompson, A. M. and Luo, M.: Retrievals of tropospheric ozone profiles from the synergism of AIRS and OMI: methodology and validation, Atmospheric Measurement Techniques, 11(10), 5587–5605, doi:10.5194/amt-11-5587-2018-supplement, 2018.

Fu, D., Bowman, K. W., Worden, H. M., Natraj, V., Worden, J. R., Yu, S., Veefkind, P., Aben, I., Landgraf, J., Strow, L. and Han, Y.: High-resolution tropospheric carbon monoxide profiles retrieved from CrIS and TROPOMI, Atmospheric Measurement Techniques, 9(6), 2567–2579, doi:10.5194/amt-9-2567-2016-supplement, 2016.

Fu, D., Worden, J. R., Liu, X., Kulawik, S. S., Bowman, K. W. and Natraj, V.: Characterization of ozone profiles derived from Aura TES and OMI radiances, Atmospheric Chemistry and Physics, 13(6), 3445–3462, doi:10.5194/acp-13-3445-2013, 2013.

Galewsky, J., Larsen, H. S., Field, R. D., Worden, J. R., Risi, C. and Schneider, M.: Stable isotopes in atmospheric water vapor and applications to the hydrologic cycle, Rev. Geophys., doi:10.1002/2015RG000512, 2016.

Good, S. P., Noone, D. and Bowen, G.: Hydrologic connectivity constrains partitioning of global terrestrial water fluxes, Science, 349(6244), 175–177, doi:10.1126/science.aaa5931, 2015.

Deleted: .

Deleted: .

Deleted: .

Deleted: .

Deleted: .

Deleted:

Deleted: .

Deleted: Galewsky, J., Larsen, H. S., Field, R. D., Worden, J. R., Risi, C. and Schneider, M.: Stable isotopes in atmospheric water vapor and applications to the hydrologic cycle, Rev. Geophys., doi:10.1002/2015RG000512, 2016.¶
¶

Formatted: Font: Times

Deleted: Eldering, A., S. S. Kulawik, J. Worden, K. Bowman, and G. Osterman (2008), Implementation of cloud retrievals for TES atmospheric retrievals: 2. Characterization of cloud top pressure and effective optical depth retrievals, *J. Geophys. Res*, *113*(D16), D16S37, doi:10.1029/2007JD008858.¶

Formatted: Font: Times

Deleted: Frankenberg, C., Wunch, D., Toon, G., Risi, C., Scheepmaker, R., Lee, J.-E., Wennberg, P. and Worden, J.: Water vapor isotopologue retrievals from high-resolution GOSAT shortwave infrared spectra, Atmos. Meas. Tech., 6(2), 263–274, doi:10.5194/amt-6-263-2013, 2013.¶

Formatted: Font: Times

Deleted: Fu, D., Kulawik, S. S., Miyazaki, K., Bowman, K. W., Worden, J. R., Eldering, A., Livesey, N. J., Teixeira, J., Irion, F. W., Herman, R. L., Osterman, G. B., Liu, X., Levelt, P. F., Thompson, A. M., and Luo, M.: Retrievals of Tropospheric Ozone Profiles from the Synergic Observation of AIRS and OMI: Methodology and Validation, Atmos. Meas. Tech. Discuss., https://doi.org/10.5194/amt-2018-138, in review, 2018.¶

Formatted: Font: Times

Deleted: Fu, D., Bowman, K. W., Worden, H. M., Natraj, V., Worden, J. R., Yu, S., Veefkind, P., Aben, I., Landgraf, J., Strow, L., and Han, Y.: High-resolution tropospheric carbon monoxide profiles retrieved from CrIS and TROPOMI, Atmos. Meas. Tech., 9, 2567-2579, https://doi.org/10.5194/amt-9-2567-2016, 2016.¶

Formatted: Font: Times

Deleted: Fu, D., Worden, J. R., Liu, X., Kulawik, S. S., Bowman, K. W., and Natraj, V.: Characterization of ozone profiles derived from Aura TES and OMI radiances, Atmos. Chem. Phys., 13, 3445-3462, https://doi.org/10.5194/acp-13-3445-2013, 2013.¶

Formatted: Font: Times

Formatted: Font: Times

Han, Y., Revercomb, H., Cromp, M., Gu, D., Johnson, D., Mooney, D., Scott, D., Strow, L., Bingham, G., Borg, L., Chen, Y., DeSlover, D., Esplin, M., Hagan, D., Jin, X., Knuteson, R., Motteler, H., Predina, J., Suwinski, L., Taylor, J., Tobin, D., Tremblay, D., Wang, C., Wang, L., Wang, L. and Zavyalov, V.: Suomi NPP CrIS measurements, sensor data record algorithm, calibration and validation activities, and record data quality, Journal of Geophysical Research-Atmospheres, 118(22), 12,734–12,748, doi:10.1002/2013JD020457, 2013.

Herman, R. L., Cherry, J. E., Young, J., Welker, J. M., Noone, D., Kulawik, S. S. and Worden, J.: Aircraft validation of Aura Tropospheric Emission Spectrometer retrievals of HDO / H_2O, Atmospheric Measurement Techniques, 120, 3127–3138, doi:10.5194/amt-7-3127-2014, 2014.

Irion, F. W., Kahn, B. H., Schreier, M. M., Fetzer, E. J., Fishbein, E., Fu, D., Kalmus, P., Wilson, R. C., Wong, S. and Yue, Q.: Single-footprint retrievals of temperature, water vapor and cloud properties from AIRS, Atmospheric Measurement Techniques, 11(2), 971–995, doi:10.1117/12.615244, 2018.

Kulawik, S. S., Worden, J., Eldering, A., Bowman, K., Gunson, M., Osterman, G. B., Zhang, L., Clough, S. A., Shephard, M. W. and Beer, R.: Implementation of cloud retrievals for Tropospheric Emission Spectrometer (TES) atmospheric retrievals: part 1. Description and characterization of errors on trace gas retrievals, Journal of Geophysical Research-Atmospheres, 111, D24204, doi:10.1029/2005JD006733, 2006.

Kulawik, S. S., Bowman, K. W., Luo, M., Rodgers, C. D. and Jourdain, L.: Impact of nonlinearity on changing the a priori of trace gas profile estimates from the Tropospheric Emission Spectrometer (TES), Atmospheric Chemistry Physics, 8, 3081–3092, 2008.

Kulawik, S. S., Worden, J. R., Wofsy, S. C., Biraud, S. C., Nassar, R., Jones, D. B. A., Olsen, E. T., Jiménez, R., Park, S., Santoni, G. W., Daube, B. C., Pittman, J. V., Stephens, B. B., Kort, E. A., Osterman, G. B.TES team: Comparison of improved Aura Tropospheric Emission Spectrometer CO_2 with HIPPO and SGP aircraft profile measurements, Atmospheric Chemistry and Physics, 13(6), 3205–3225, doi:10.5194/acp-13-3205-2013, 2013.

Lacour, J. L., Risi, C., clarisse, L., Bony, S., hurtmans, D., Clerbaux, C. and Coheur, P.-F.: Mid-tropospheric δD observations from IASI/MetOp at high spatial and temporal resolution, Atmospheric Chemistry and Physics, 12(22), 10817–10832, doi:10.5194/acp-12-10817-2012, 2012.

Lacour, J.-L., Risi, C., Worden, J., Clerbaux, C. and Coheur, P.-F.: Importance of depth and intensity of convection on the isotopic composition of water vapor as seen from IASI and TES δ D observations, Earth and Planetary Science Letters, 481, 387–394, doi:10.1016/j.epsl.2017.10.048, 2018.

Lamouroux, J., Régalia, L., Thomas, X., Vander Auwera, J., Gamache, R. R., Hartmann, J-M.: CO2 line-mixing database and software update and its tests in the 2.1 μm and 4.3 μm regions, Journal Quantitative Spectroscopy Radiative Transfer, 151, 88-96, 2015

Formatted: Font: Times

Deleted: Han, Y., et al.: Suomi NPP CrIS measurements, sensor data record algorithm, calibration and validation activities, and record data quality. J. Geophys. Res. Atmos., 118, 12 734–12 748, doi:10.1002/2013JD020344¶

Formatted: Font: Times

Formatted: Font: Times

Formatted: Font: Times, 12 pt

Formatted: Font: Times

Deleted: Herman, R. L., J. E. Cherry, J. Young, J. M. Welker, D. Noone, S. S. Kulawik, and J. Worden (2014), Aircraft validation of Aura Tropospheric Emission Spectrometer retrievals of HDO / H_2O, *Atmos. Meas. Tech.*, *120*, 3127–3138, doi:10.5194/amt-7-3127-2014.¶

Formatted: Font: 12 pt

Formatted: Font: Times

Deleted: Irion, F. W., Kahn, B. H., Schreier, M. M., Fetzer, E. J., Fishbein, E., Fu, D., Kalmus, P., Wilson, R. C., Wong, S. and Yue, Q.: Single-footprint retrievals of temperature, water vapor and cloud properties from AIRS, Atmos. Meas. Tech., 11(2), 971–995, doi:10.1117/12.615244, 2018.¶

Formatted: Font: Times

Deleted: J. Geophys. Res

Formatted: Font: Times

Formatted: Font: Times

Deleted: .

Deleted: t.

Deleted: .

Deleted: .

Deleted: .

Luo, M., Rinsland, C. P., Rodgers, C. D., Logan, J. A., Worden, H., Kulawik, S., Eldering, A., Goldman, A., Shephard, M. W., Gunson, M. and Lampel, M.: Comparison of carbon monoxide measurements by TES and MOPITT: Influence of a priori data and instrument characteristics on nadir atmospheric species retrievals, Journal of Geophysical Research-Atmospheres , 112(D9), D09303, doi:10.1029/2006JD007663, 2007.

Moncet, J-L., G. Uymin, A. E. Lipton, and H. E. Snell: Infrared radiance modeling by optimal spectral sampling. J. Atmos. Sci., 65, 3917–3934, doi: 10.1175/2008JAS2711.1, 2008

Moncet, J-L., Uymin, G., Liang, P. and Lipton, A.E: Fast and accurate radiative transfer in the thermal regime by simultaneous optimal spectral sampling over all channels. Journal of the Atmospheric Sciences, vol 72, 2622-2641, doi: 0.1175/JAS-D-14-0190.1, 2015

Noone, D., Galewsky, J., Sharp, Z. D., Worden, J., Barnes, J., Baer, D., Bailey, A., Brown, D. P., Christensen, L., Crosson, E., Dong, F., Hurley, J. V., Johnson, L. R., Strong, M., Toohey, D., Van Pelt, A. and Wright, J. S.: Properties of air mass mixing and humidity in the subtropics from measurements of the D/H isotope ratio of water vapor at the Mauna Loa Observatory, Journal Geophysical Research-Atmospheres, 116(D22), D22113, doi:10.1029/2011JD015773, 2011.

Pagano, T. S., Aumann, H. H., Hagan, D. E., and Overoye, K.: Prelaunch and in-flight radiometric calibration of the Atmospheric Infrared Sounder (AIRS), IEEE Transactions on Geoscience and Remote Sensing, 41, 265–273, 2003.

Pagano, T. S., Aumann, H. H., Schindler, R., Elliott, D., Broberg, S., Overoye, K., and Weiler, M. H.: Absolute radiometric calibration accuracy of the Atmospheric Infrared Sounder (AIRS), in: Proc. SPIE, vol. 7081, doi:10.1117/12.795445, 2008.

Payne, V. H., Alvarado, M. J., Cady-Pereira, K. E., Worden, J. R., Kulawik, S. S. and Fischer, E. V.: Satellite observations of peroxyacetyl nitrate from the Aura Tropospheric Emission Spectrometer, Atmospheric Measurement Techniques, 7(11), 3737–3749, doi:10.5194/amt-7-3737-2014, 2014.

Rodgers, C. D. and Connor, B. J.: Intercomparison of remote sounding instruments, Journal of Geophysical Research-Atmospheres, 108, 4116, doi:10.1029/2002JD002299, 2003.

Risi, C., Noone, D., Worden, J., Frankenberg, C., Stiller, G., Kiefer, M., Funke, B., Walker, K., Bernath, P., Schneider, M., Wunch, D., Sherlock, V., Deutscher, N., Griffith, D., Wennberg, P. O., Strong, K., Smale, D., Mahieu, E., Barthlott, S., Hase, F., García, O., Notholt, J., Warneke, T., Toon, G., Sayres, D., Bony, S., Lee, J., Brown, D., Uemura, R. and Sturm, C.: Process-evaluation of tropospheric humidity simulated by general circulation models using water vapor isotopologues: 1. Comparison between models and observations, Journal of Geophysical Research-Atmospheres , 117(D5), D05303, doi:10.1029/2011JD016621, 2012.

Risi, C., Noone, D., Frankenberg, C. and Worden, J.: Role of continental recycling in intraseasonal variations of continental moisture as deduced from model simulations and water

Formatted: Font: Times

Deleted: J. Geophys. Res

Deleted: ¶
Moncet, J-L. et al: Algorithm theoretical basis document for the Cross Track Infrared Sound er (CrIS). Volume II, Environmental Data Records (EDR), version 4.2. AER Tech. Doc. P1187-TR-I-08, 298 pp. [Available online at¶
http://npp.gsfc.nasa.gov/sciencedocuments/2013-01/474-00056_RevABaseline.pdf.], 2005¶

Deleted: Noone, D. et al. (2011), Properties of air mass mixing and humidity in the subtropics from measurements of the D/H isotope ratio of water vapor at the Mauna Loa Observatory, *J. Geophys. Res*, *116*(D22), D22113, doi:10.1029/2011JD015773.¶

Formatted: Font: 12 pt

Formatted: Font: Times

Formatted: Font: 12 pt, Not Bold

Formatted: Font: Times, 12 pt, Not Bold

Deleted: IEEE T. Geosci. Remote

Formatted: Font: 12 pt, Not Bold

Formatted: Pattern: Clear (White)

Formatted: Font: Times New Roman

Formatted: Font: Times

Deleted: Atmos. Meas. Tech.

Formatted: Font: Times

Deleted: J. Geophys. Res

Formatted: Font: Times

vapor isotopic measurements, Water Resour. Res., 49(7), 4136–4156, doi:10.1002/wrcr.20312, 2013.

Rothman, L. S., I. E. Gordon, Y. Babikov et al., "The HITRAN 2012 Molecular Spectroscopic Database", *Journal of Quantitative Spectroscopy and Radiative Transfer* **130**, 4-50 (2013)

Schneider, M., Barthlott, S., Hase, F., González, Y., Yoshimura, K., García, O. E., Sepúlveda, E., Gomez-Pelaez, A., Gisi, M., Kohlhepp, R., Dohe, S., Blumenstock, T., Wiegele, A., Christner, E., Strong, K., Weaver, D., Palm, M., Deutscher, N. M., Warneke, T., Notholt, J., Lejeune, B., Demoulin, P., Jones, N., Griffith, D. W. T., Smale, D. and Robinson, J.: Ground-based remote sensing of tropospheric water vapour isotopologues within the project MUSICA, Atmospheric Measurement Techniques , 5(12), 3007–3027, doi:10.5194/amt-5-3007-2012, 2012.

Shephard, M. W., Worden, H. M., Cady-Pereira, K. E., Lampel, M., Luo, M., Bowman, K. W., Sarkissian, E., Beer, R., Rider, D. M., Tobin, D. C., Revercomb, H. E., Fisher, B. M., Tremblay, D., Clough, S. A., Osterman, G. B. and Gunson, M.: Tropospheric Emission Spectrometer nadir spectral radiance comparisons, Journal of Geophysical Research-Atmospheres , 113(D15), D15S05, doi:10.1029/2007JD008856, 2008.

Shephard, M. W. and Cady-Pereira, K. E.: Cross-track Infrared Sounder (CrIS) satellite observations of tropospheric ammonia, Atmospheric Measurement Techniques, 8(3), 1323–1336, doi:10.5194/acpd-15-4823-2015, 2015.

Strow, L. L., Hannon, S., Weiler, M., Overoye, K., Gaiser, S. L., Aumann, H. H.: Prelaunch spectral calibration of the atmospheric infrared sounder (AIRS), IEEE Transactions Geoscience and Remote Sensing, 41(2), 274-286, doi: 10.1109/TGRS.2002.808245, 2003

Tran, H., Flaud J-M, Gabard, T., Hase, F., Von Clarmann, T., Camy-Peyret, C., Payan, S., Hartmann, J-M.: Model, software, and database for line-mixing effects in the n_3 and n_4 bands of CH_4 and tests using laboratory and planetary measurements. I. N_2 (and air) broadenings and the Earth atmosphere, Journal Quantitative Spectroscopy Radiative Transfer, 101, 284-305, 2006

Worden, J., Kulawik, S., Shepard, M., Clough, S., Worden, H., Bowman, K. and Goldman, A.: Predicted errors of tropospheric emission spectrometer nadir retrievals from spectral window selection, Journal of Geophysical Research-Atmospheres, 109(D9), D09308, doi:10.1029/2004JD004522, 2004.

Worden, J., Bowman, K., Noone, D., Beer, R., Clough, S., Eldering, A., Fisher, B., Goldman, A., Gunson, M., Herman, R., Kulawik, S. S., Lampel, M., Luo, M., Osterman, G., Rinsland, C., Rodgers, C., Sander, S., Shephard, M. and Worden, H.: Tropospheric Emission Spectrometer observations of the tropospheric HDO/H 2O ratio: Estimation approach and characterization, Journal of Geophysical Research-Atmospheres , 111(D16), doi:10.1029/2005JD006606, 2006.

Worden, J., Noone, D., Bowman, K., Beer, R., Eldering, A., Fisher, B., Gunson, M., Goldman, A., Herman, R., Kulawik, S. S., Lampel, M., Osterman, G., Rinsland, C., Rodgers, C., Sander, S., Shephard, M., Webster, C. R. and Worden, H.: Importance of rain evaporation and

Formatted: Font: Times

Deleted: Atmos. Meas. Tech.

Deleted: J. Geophys. Res

Formatted: Font: Times

Formatted: Font: Times

Deleted: Shephard, M. W., and K. Cady-Pereira Cross-track Infrared Sounder (CrIS) satellite observations of tropospheric ammonia, *Atmos. Meas. Tech.*, *8*, 1323-1336, doi:10.5194/amt-8-1323-2015, 2015.¶

Deleted: .

Deleted: .

Deleted: .

Deleted: 10.1109/TGRS.2002.808245,

Formatted: Font: Times

Deleted: Flaud,

Deleted: .

Deleted: .

Deleted: .

Deleted: t

Deleted: .

Deleted: f.

Formatted: Font: Times

Deleted: Worden, J., Kulawik, S., Shepard, M., Clough, S., Worden, H., Bowman, K. and Goldman, A.: Predicted errors of tropospheric emission spectrometer nadir retrievals from spectral window selection, J. Geophys. Res, 109(D9), D09308, doi:10.1029/2004JD004522, 2004.¶

Formatted: Font: Times

Deleted: J. Geophys. Res

continental convection in the tropical water cycle, Nature, 445(7127), 528–532, doi:10.1038/nature05508, 2007a.

Worden, J., D. Noone, J. Galewsky, A. Bailey, K. Bowman, D. Brown, J. Hurley, S. Kulawik, J. Lee, and M. Strong (2011), Estimate of bias in Aura TES HDO/H_2O profiles from comparison of TES and in situ HDO/H_2O measurements at the Mauna Loa observatory, *Atmospheric Chemistry and Physics*, *11*(9), 4491–4503, doi:10.5194/acp-11-4491-2011.

Worden, J., Kulawik, S., Frankenberg, C., Payne, V., Bowman, K., Cady-Peirara, K., Wecht, K., Lee, J.-E. and Noone, D.: Profiles of CH_4, HDO, H_2O, and N_2O with improved lower tropospheric vertical resolution from Aura TES radiances, Atmospheric Measurement Techniques, 5(2), 397–411, doi:10.5194/amt-5-397-2012, 2012.

Worden, J., Wecht, K., Frankenberg, C., Alvarado, M., Bowman, K., Kort, E., Kulawik, S., Lee, M., Payne, V. and Worden, H.: CH4 and CO distributions over tropical fires during October 2006 observed by the Aura TES satellite instrument and modeled by GEOS-Chem, Atmospheric Chemistry and Physics, 13(7), 3679–3692, doi:10.5194/acp-13-3679-2013, 2013.

Worden, J. R., Turner, A. J., Bloom, A., Kulawik, S. S., Liu, J., Lee, M., Weidner, R., Bowman, K., Frankenberg, C., Parker, R. and Payne, V. H.: Quantifying lower tropospheric methane concentrations using GOSAT near-IR and TES thermal IR measurements, Atmospheric Measurement Techniques, 8(8), 3433–3445, doi:10.5194/amt-8-3433-2015, 2015.

Wright, J. S., Fu, R., Worden, J. R., Chakraborty, S., Clinton, N., Risi, C., sun, Y. and Yin, L.: Rainforest-initiated wet season onset over the southern Amazon, Proceedings of the National academy of Sciences, 1–6, doi:10.1073/pnas.1621516114/-/DCSupplemental, 2017.

Xiong, X., Barnet, C., Maddy, E., Sweeney, C., Liu, X., Zhou, L. and Goldberg, M.: Characterization and validation of methane products from the Atmospheric Infrared Sounder (AIRS), Journal Geophysical Research-Biogeosciences, 113, doi:10.1029/2007JG000500, 2008.

Xiong, X., Barnet, C., Maddy, E., Wofsy, S. C., Chen, L. A., Karion, A. and Sweeney, C.: Detection of methane depletion associated with stratospheric intrusion by atmospheric infrared sounder (AIRS), Geophysical Research Letters, 40(10), 2455–2459, doi:10.1002/grl.50476, 2013.

Xiong, X., Barnet, C., Maddy, E., Sweeney, C., Liu, X., Zhou, L. and Goldberg, M.: Characterization and validation of methane products from the Atmospheric Infrared Sounder (AIRS), J. Geophys. Res, 113(null), G00A01, doi:10.1029/2007JG000500, 2008.

Zhou, L., Tian, Y., Myneni, R. B., Ciais, P., Saatchi, S., Liu, Y. Y., Piao, S., Chen, H., Vermote, E. F., Song, C. and Hwang, T.: Widespread decline of Congo rainforest greenness in the past decade, Nature, 508(7498), 86–90, doi:10.1038/nature13265, 2014.

Deleted: ¶

Formatted: Font: 12 pt

Formatted: Font: 12 pt

Formatted: Font: Times

Deleted: Atmos. Meas. Tech.

Formatted: Font: Times

Formatted: Font: Times

Deleted: Atmos. Meas. Tech.

Formatted: Font: Times

Deleted: Xiong, X., C. Barnet, E. Maddy, C. Sweeney, X. Liu, L. Zhou, and M. Goldberg (2008), Characterization and validation of methane products from the Atmospheric Infrared Sounder (AIRS), *J. Geophys. Res*, *113*(null), G00A01, doi:10.1029/2007JG000500.¶

Formatted: Font: Times

Deleted: Xiong, X., C. Barnet, E. Maddy, S. C. Wofsy, L. A. Chen, A. Karion, and C. Sweeney (2013), Detection of methane depletion associated with stratospheric intrusion by atmospheric infrared sounder (AIRS), *Geophys. Res. Lett*, *40*(10), 2455–2459, doi:10.1002/grl.50476.¶

Deleted: ……………Page Break……………
¶

Formatted: Font: Times

Formatted: Font: Times

Deleted: ¶

Table 1: Comparison between averaged TES and AIRS HDO/H_2O ratio (750-350 hPa). The units are in parts per thousand relative to Standard Mean Ocean Water. The second column shows the expected RMS based on the uncertainties of the TES and AIRS data. The third column shows the actual RMS difference between TES and AIRS. The last column shows the mean difference.

Date	Expected RMS (per mil / SMOW)	Actual RMS (per mil / SMOW)	Mean (TES-AIRS) (per mil / SMOW)
2006-06-01	31.1	30.6	-2.7 +/- 1.5
2007-06-02	30.0	31.9	-0.6 +/- 1.5
2008-06-02	31.5	29.3	0.5 +/- 1.4
2009-07-06	31.6	27.1	0.7 +/- 1.4
2010-06-02	31.6	28.2	3.7 +/- 1.2

Moved (insertion) [2]

Deleted: The last row shows the average and RMS for the mean differences in the far right column.

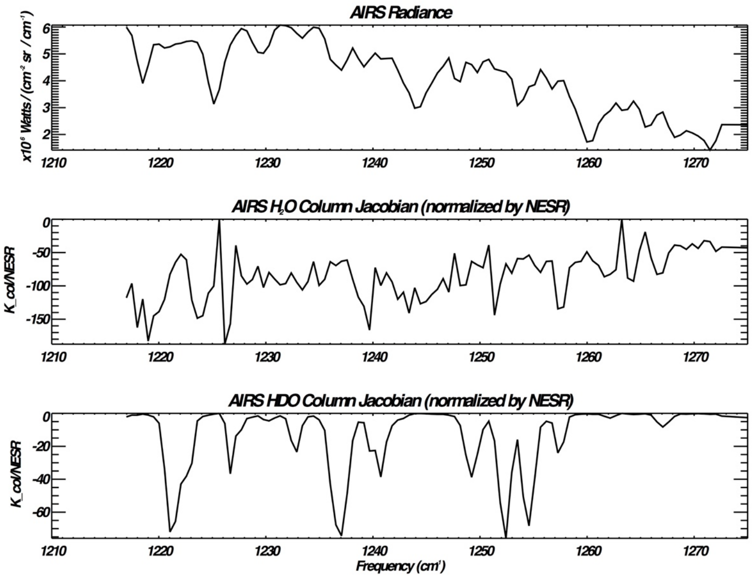
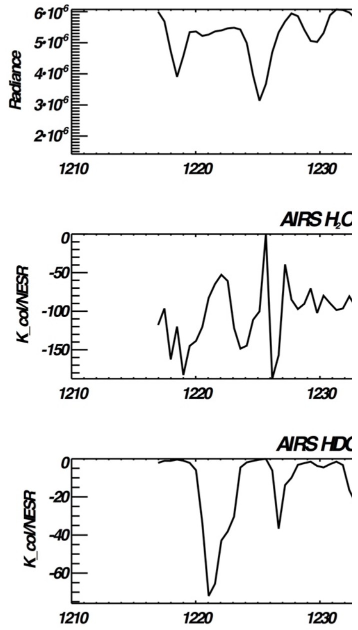


Figure 1: (top) AIRS radiance at approximately 8 microns for a typical tropical scene. (middle) The total column (log) Jacobian for H_2O normalized by the AIRS NESR. (bottom) The total column (log) Jacobian for HDO normalized by the AIRS NESR.



Deleted:

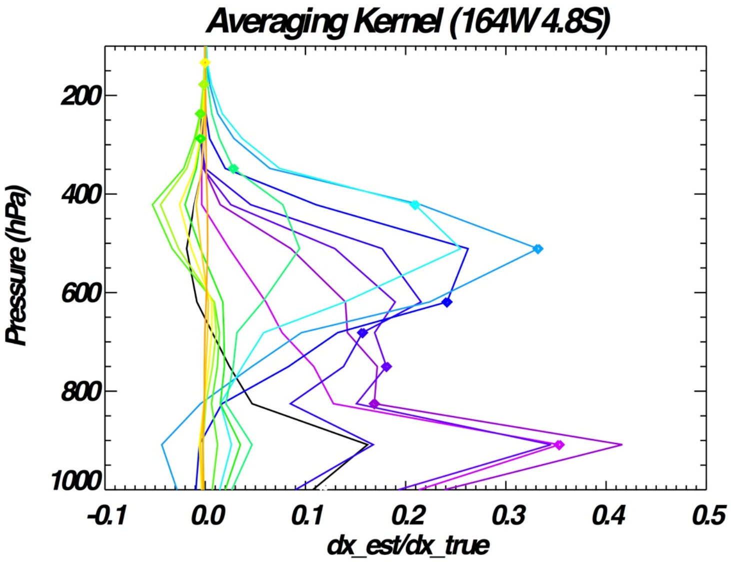
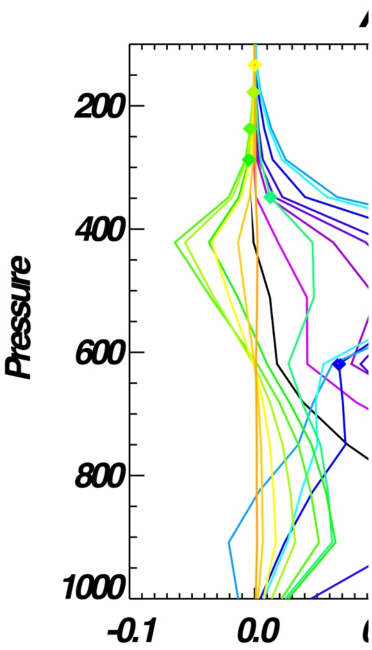
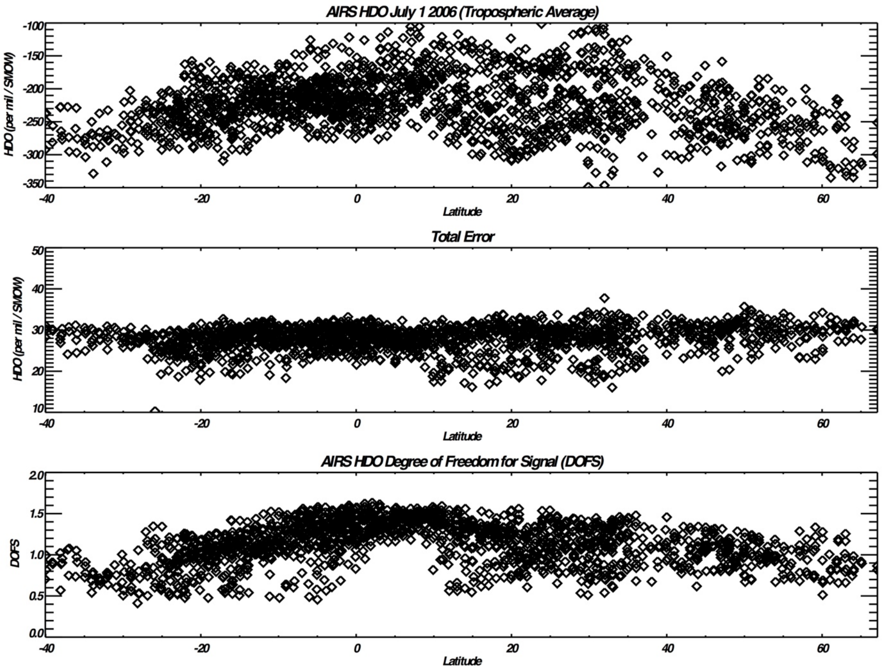


Figure 2: The rows of the averaging kernel matrix for the HDO retrieval corresponding to the radiance shown in Figure 1. The different colors and symbols are used to indicate the pressure levels corresponding to each row of the averaging kernel matrix.



Deleted:


AIRS HDO July 1 2006 (Tropospheric Average)

Total Error

AIRS HDO Degree of Freedom for Signal (DOFS)

Figure 3: (top) The mean tropospheric deuterium content (in “per mil” or units of parts per thousand relative to the deuterium content of the ocean or SMOW) for June 1 2006 as inferred from AIRS radiance measurements. (middle) The total error for the measurements in the top panel (also in units of per mil relative to SMOW). (bottom) The DOFS for the retrieval.

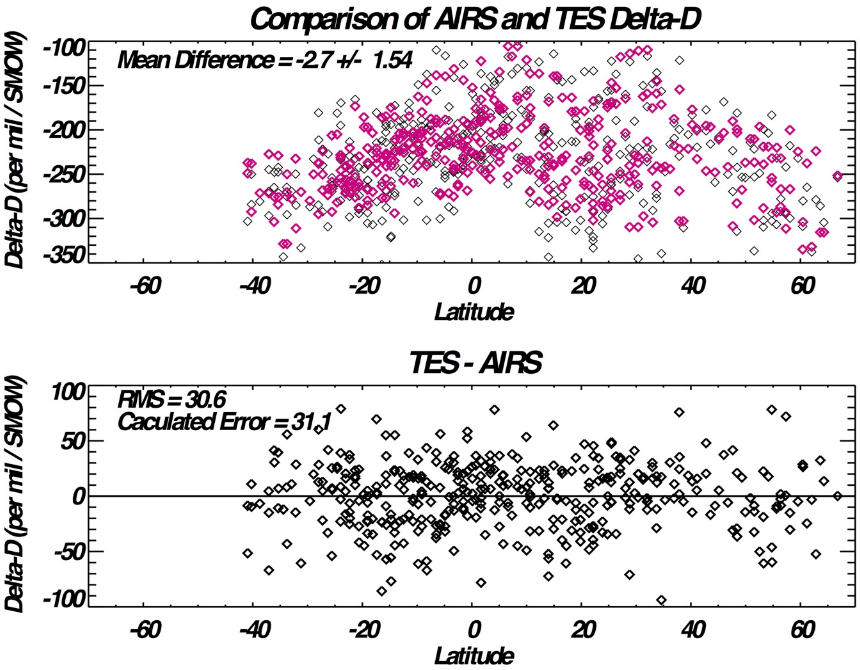


Figure 4: (top) Comparison of AIRS (red) and TES (black) delta-D for June 1 2006 (~600 co-located observations). (bottom) The differences (after bias subtraction) between TES and AIRS delta-D measurements.

Deleted: d

Deleted: t

Deleted: ----------Page Break---------- ¶

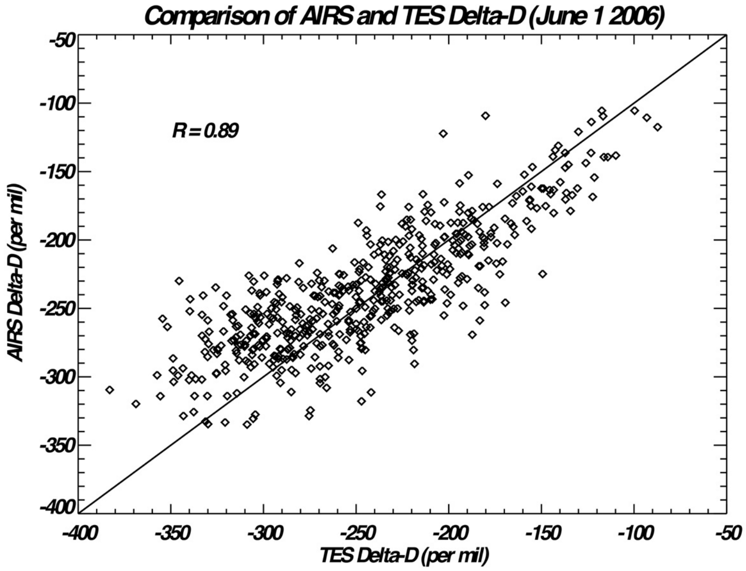
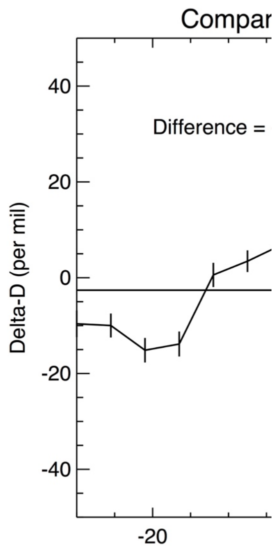


Figure 5: Comparison of the AIRS and TES deuterium content. The solid line is the one-to-one line.

Deleted:



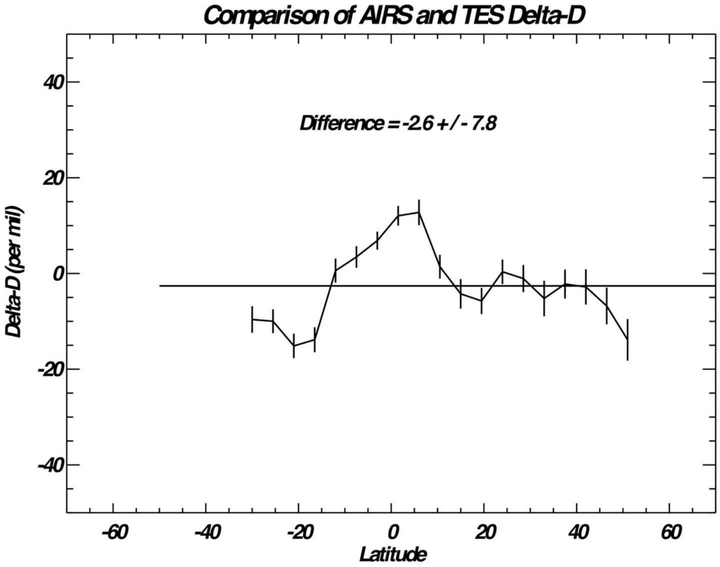


Figure 6: The Latitudinal differences between TES and AIRS Delta-D using co-located observations for 5 days (approximately 600 observations per day) of data, spaced over 5 Northern Hemisphere summers between 2006 and 2010.

Deleted: 5

Deleted: Comparison of

Deleted: t

Deleted: summers

I would like to greatly thank both reviewers for their detailed review and comments. Reviewing and editing these papers is quite a bit of (effectively voluntary) work and both reviews really went into great detail on fixing the presentation. With respect to the comment on “minimalism”, I actually was striving for minimalism in this paper but apparently overshot my goal! ☺. For example, I did not want to write (yet) another paper full of the optimal estimation description in all of its gory, (or glory?) equation detail but instead report on the basic notions….. that the AIRS radiances can be used to generation global deuterium content retrievals and that their vertical resolution is about the same as TES but with slightly poorer uncertainties, and that we will soon produce a long record of the data that spans most of the globe and can hopefully produce scientific awesomeness.

Again, thanks for the review. Below are the comments and my responses.

Response to Reviewer 1

General Comment: This study presents the application of an existing retrieval methodology of HDO/H2O vertical profiles originally applied on TES, on AIRS thermal infrared measurements. The authors briefly remind the retrieval methodology, describe the error and sensitivity, and show a comparison with co-located TES retrievals. In my view, this is a welcome study as the capabilities of AIRS sensors for HDO/H2O ratio retrievals were unknown/not tested, and the sampling characteristics of AIRS offer great potential for isotopes related studies. The manuscript is short and generally convincing but the presentation is too minimalist and should be improved. Some discussions on previous improvements in characterizing HDO/H2O-H2O pairs retrieval is missing. I list a few comments which should be easily resolved by the authors.

Specific Comments:

- Introduction: A short introduction on water isotopes, their usefulness and a description on what are the remote sensing capabilities to observe HDO/H2O ratios in the free troposphere would be useful to strengthen the importance of this work and to smooth the feeling of reading a purely technical report.

  Response: I added a paragraph at the front that describes a bit of history on water isotope measurements, and how these vapor based measurements have helped address global water / carbon questions.

- P2, Line 19: estimates of HDO/H2O ratios and not HDO

  Response: Added “and their ratio”. We actually do retrieve HDO and H_2O seaparately even if the retrieval setup optimizes the ratio.

- P2, Line 20: Why only summertime TES global survey’s? Do you mean boreal summertime?

  Response: added boreal and added a statement about current limited processing capabilities

- P2, Line 23: “We then compare the AIRS and TES data to evaluate and quantify the calculated uncertainties of the AIRS data” - To evaluate and quantify the calculated uncertainties sound a little odd. This needs to be rephrased.

  Response: removed “and quantify”

- This paper is relatively short and yet there is a lot of statements about futures publications (P2, L17-18;P2, L23-24;P5, L29 – P6,L8). Some of them could be removed.

  Response: Removed most of these references where appropriate and modified some of the language about the utility of the 12 micron band for constraining atmospheric temperature.

- P3, L8: There is a redundancy here of the statement that TES is part of the A-Train, it was just said in the previous sentence.

  Response removed

- P5, L9: “This retrieval algorithm can use radiances (..) to quantify and characterize geophysical observables appropriate for the corresponding radiance.” – What is an appropriate geophysical observable? To retrieve different geophysical parameters?

  Response: changed “appropriate” to “that affect”. I think this wording is appropriate but terse. I can also add another line such as (e.g. the ozone concentrations affect radiances in the 9.6 micron ozone band) but that seems too wordy.

- P5, L16-17: "in order to ensure that [the retrieval of] the ratio is optimized, as opposed (..)" [missing]

  Response fixed

- P5, L29 – P6,L8: All this part describes the importance of including the 12 microns radiances for the methane retrieval. That is not interesting in the frame of this paper.

  Response (fixed in above response, hopefully ☺).

- P6, L17-19: Jacobians have not be defined. What does the -50 treshold represent? How is it calculated?

  Response: I added the definition for a Jacobian and changed the language around.. basically 2% is equivalent to 1/50… 1% = 1/100 etc.

- P6, L22: “(..) partial derivative of the estimate relative to [partial derivative] of the true state”. Or maybe in a language more accessible to potential users not familiar with optimal estimation: “the response of the retrieved state to perturbations of the true state”

  Response: changed

- P6, L23: It is confusing to translate the example in terms of HDO/H2O ratios since the averaging kernels are for HDO.

  Response thanks for pointing this one out.. I adjusted the language accordingly and added a sentence about how the information about HDO/H_2O is limited by HDO; I also added a reference.

- P6, L28-29: Schneider et al., 2012 proposed an a posteriori methodology to characterize the joint retrieval of H2O and HDO. The method allows to transform the products obtained in the log(H2O),log(HDO) space into a proxy state log(H2O),δD which is very useful for characterization. Moreover, the HDO/H2O ratio product is often used in pair with H2O it is therefore important to discuss the differences of sensitivity of H2O and HDO/H2O ratios. This is missing here.

  Response I added language on how the averaging kernels for H_2O are different than that for HDO and that Schneider et al discusses an approach to use these data with simple models while accounting for the different sensitivities.

- P7, L13-L15: There are a lot of measurements within the tropics with DOFS between 0.5 and 1 so I wouldn't generalize this situation to the whole tropics. This might be valid only for the averaging kernels shown.

  Response: adjusted the language .. now we say "many" which implies "not all"

- P8, L6->L11: All this part would better fit in the error characterization part

  Response: moved

- Comparisons of AIRS and TES retrievals - In order to be really convincing, this part needs to be completed.

  – Would it be possible to show a scatter plot of AIRS versus TES?

- – What is the correlation between AIRS and TES retrievals?

  Response: I am not that convinced this is a meaningful figure as it is the difference between AIRS and TES that can be used to determine if the AIRS data is (relatively) well characterized. Having said that I have included it here in case readers find it useful. The correlation for this day is 0.89.

- – Because this kind of product is used in pairs with humidity retrievals it is also interesting to show that both sounders show the same humidity-δD information and not only δD.

  Response: I dont think this comparison is of use to this specific paper as it shows that the pairs generated by AIRS are similar to those from TES but slightly different, as expected because the sensitivity and errors are different. For this reason I would prefer not to show here, but will show in subsequent papers when we start looking at the science!

- – I didn't understand the error assessment reasoning. The mean bias across latitude is -2.6 permil, later on the authors assess the RMS to be 7.8 permil then the authors say the accuracy is 7.8 permil. Is this a mistake or do I miss something? The language between accuracy and precision should be clarified.
- – What about the latitudinal variations of the bias which are greater (-15 to 15 permil) than the mean standard error? It looks like there is a latitudinal bias, could it be caused by some dependence on temperature or humidity content?

Response: I attempted to clean up the language here, hopefully it's a bit more clear! I also added language that the latitudinal variations are typically due to uncertainties in temperature, water vapor, and spectroscopy, as well as differences in the vertical resolution.

- – Could you plot the data in Figure 5 until 40°S as in the previous figure?

Response: Done!

- The conclusions could be more developed. One of the interest of this paper lies in the development of a HDO retrieval methodology from AIRS data which was unknown and opens great perspectives for users interested in such measurements. In this context, a word on the future plans of the authors on processing more AIRS data, or not, would be interesting.

Response: Added a paragraph on current and future plans with respect to building an ESDR.

- P9, L8: Please reference the natural variability of δD

Response: Added statement about Figure 3 and cited a TES paper.

Technical corrections

• Abstract, L17: Northern instead of N; • P1, L28: a verb is missing (fixed)

- L29, degrees (fixed)

- P4 , L30 : Description of Retrieval Approach -> Description of the retrieval approach (fixed)
- P5, L29 : (e.g. Figures 1-4). (fixed)
- P7, L4: add degrees to latitude (fixed)
- P7, L8: use the delta Greek notation δ (this is stylistic, I have added "or δ" instead)
- Figure 4: A legend is missing, what is TES and what is AIRS? (fixed)

Reviewer 2

General Comment

As this study is targeting the preparation of a new Earth Science Data Record covering AIRS HDO/H2O observations, it clearly has a high scientific significance. The manuscript itself is clear and concise, but I would agree with Reviewer #1 that the presentation is indeed somewhat "minimalistic" and could be extended and improved. Please carefully follow suggestions and comments provided by Reviewer #1 and those listed below so that the paper can be published soon.

Specific comments

- p3, l4: The AIRS swath width is 1650 km (Aumann et al., 2003) rather than 1250 km.

Response: (fixed)

- p5, l25-26: Although the AIRS noise is characterized well for individual channels, in other work I noticed noise can be spectrally correlated between neighboring channels, which is due to the 1-D linear detector arrays of AIRS sharing the same electric module (Pagano et al., 2008). This may be too specific to discuss in your paper; I just wondered if you considered this?

Response: We have not explicitly addressed this issue and in fact the same is true with the TES data because the data are apodized but the calculated errors assume the noise is random (or not apodized). On the other hand the apodization is accounted for in the TES retrievals when we calculate the forward model radiance. In contrast with the TES data where we can account for the apodiziation it is not clear how to account for these noise correlations in the AIRS data. Instead we added a statement that the noise is assumed to be random as we are unable to account for correlations between channels. The effect of this assumption is that the calculated errors will be too large and is therefore a conservative estimate of the uncertainties.

Pagano, T. S., Aumann, H. H., Schindler, R., Elliott, D., Broberg, S., Overoye, K., and Weiler, M. H.: Absolute radiometric calibration accuracy of the Atmospheric Infrared Sounder (AIRS), in: Proc. SPIE, vol. 7081, doi:10.1117/12.795445, 2008.

- p7, l20-29: Are the HDO retrieval results correlated with the simultaneous H2O re-trievals? Does the AVK matrix show any correlations between these retrieval variables?

Response: Yes! These correlations are addressed 1) in model comparisons by applying the averaging kernels for both HDO and H_2O to the model (e.g. Risi *et al*. 2013) or 2) by calculating the resulting error (e.g. Worden *et al*. 2006) and including that in the error budget, or mitigating further by 3) projecting to HDO-H_2O pairs as discussed by the first reviewer. I have discussed the pairing approach based on the first reviewers comments and will add the Risi reference as well.

Fig. 2: Maybe show also the integral of the AVKs, to indicate the amount of measurement information in the retrieval results? (Fix "are _used_ to indicate" in the caption.)

Response: Fixed caption. The integral of the AVKs (or trace actually) is shown in the bottom panel of Figure 3 and discussed in the text.

Fig. 4: A legend/definition of the colors used for the plot on the top seems to be missing.

Response: Fixed!

Technical corrections
p1, l17: N. -> Northern (also in other places) (fixed)
p1, l22: ...reduced spectral resolution _of AIRS_ (for clarity?) (removed sentence as it was confusing to have in the abstract)

p1, l24: Suggest to remove reference (Worden et al., 2004) from abstract. p1, l27-28: Please fix incomplete sentence. (see above)

p1, l29: Add degree symbols to "30 S and 50 N" (also in other places)? I have added the word “degrees” instead.

p2, l2: The copyright statement "All rights reserved." is not allowed in the given form, I think, please see https://www.atmospheric-measurement- techniques.net/about/licence_and_copyright.html for details.

Response: I have to use this copyright for JPL during the submission phase. Once / if the paper is accepted I put in another form where JPL puts in a modification to the Copernicus agreement.

p2, l4: "Introduction:" -> "Introduction" p3, l11: PAN, -> PAN _

fixed

p3, l22: Earth Science Data Records (ESDR’s) -> ESDR’s (acronym was already introduced)

fixed

p4, l25: "a version of the v4 AIRS" -> "version 4 of the AIRS" (?) (fixed)

p5, l6: will _only briefly_ summarize (?) (fixed)

p5, l9-10: Not sure if "...appropriate for the corresponding radiance." is a good phrase here?

(changed, see comment from reviewer 1)

p6, l4-6: Remove redundant sentence. (fixed) p6, l31: Change date format to "1 July 2016" (also in other places); I think this is a US Versus Europe date thing ☺. Can I keep as is? Its like asking me to drive in the left lane ☺.

p7, l2: we can only (?) (fixed)

p8, l14: indicate s (fixed)

Page 10: [1] Deleted **Microsoft Office User** **11/14/18 3:40:00 AM**