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Water vapor isotopologues retrievals from high resolution GOSAT short-wave infrared spectra

C. Frankenberg[1], D. Wunch[2], G. Toon[1], C. Risi[3], R. Scheepmaker[4], J.-E. Lee[1], P. Wennberg[2], and J. Worden[1]

[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, USA
[2]California Institute of Technology, Pasadena, USA
[3]LMD/IPSL, CNRS, Paris, France
[4]SRON Netherlands Institute for Space Research, Utrecht, The Netherlands

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Correspondence to: C. Frankenberg (christian.frankenberg@jpl.nasa.gov)

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Abstract

Remote sensing of the isotopic composition of water vapor can provide valuable information on the hydrological cycle. Here, we demonstrate feasibility of retrievals of the relative abundance of HDO (the HDO / H_2O ratio) from the Japanese GOSAT satellite. For this purpose, we use high spectral resolution nadir radiances around 6400 cm^{-1} (1.56 µm) to retrieve vertical column amounts of H_2O and HDO. Retrievals of H_2O correlate well with ECMWF (European Centre for Medium-Range Weather Forecasts) integrated profiles ($r^2 = 0.96$). Typical precision errors in the retrieved column averaged deuterium depletion (δD) are 20–40 ‰. We validate δD against a TCCON (Total Carbon Column Observing Network) ground-based station in Lamont, Oklahoma. Using retrievals in very dry areas over Antarctica, we detect a small systematic offset in retrieved H_2O and HDO column amounts and take this into account for a bias-correction of δD. Monthly averages of δD in the June 2009 to September 2011 time-frame are well correlated with TCCON ($r^2 = 0.79$) and exhibit a slope of 0.98 (1.23 if not bias corrected). We also compare seasonal averages on the global scale with results from the SCIAMACHY instrument in the 2003–2005 timeframe. Despite the lack of temporal overlap, seasonal averages in general agree well, with spatial correlations (r^2) ranging from 0.62 in September through November to 0.83 in June through August. However, we observe higher variability in GOSAT δD, indicated by fitted slopes between 1.2 and 1.46. The discrepancies are likely related to differences in vertical sensitivities but warrant further validation of both GOSAT and SCIAMACHY and an extension of the validation dataset.

1 Introduction

Significant uncertainties in current climate model predictions of future warming are associated with the hydrological cycle, such as water vapor and cloud feedbacks (Held and Soden, 2006; Randall et al., 2007). For example, the variations in boundary layer

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cloud distribution are the largest source of spread in climate change projections (Bony and Dufresne, 2005; Bony et al., 2006).

Atmospheric general circulation models (GCMs) must therefore accurately simulate the processes that control tropospheric humidity and clouds correctly for their climate change predictions to be credible.

Measurements of stable isotopologues of water can provide key constraints on the processes controlling clouds and humidity because (1) the isotopic composition of water will change as the water changes phase, (2) water sources such as the ocean and plants have different isotopic signatures (or compositions), and (3) mixing processes will affect the isotopic composition of water differently than phase changes. In the upper-troposphere, the water vapor isotopic composition can be measured by satellites (Kuang et al., 2003; Nassar et al., 2007; Steinwagner et al., 2010) or in-situ (Webster and Heymsfield, 2003; Sayres et al., 2010) and reflects the role of convection in the transport of water in the upper-troposphere and through the tropopause (Moyer et al., 1996). In the mid-troposphere, the water vapor isotopic composition can also be measured by satellite (Worden et al., 2007; Herbin et al., 2009; Schneider and Hase, 2011) and in-situ (Noone et al., 2011) and may give an indication about water cycle processes such as mixing of air masses (Galewsky and Hurley, 2010) or rain reevaporation (Worden et al., 2007). In the lower troposphere, the water vapor isotopic composition is sensitive to the origin of water vapor and precipitation, such as continental recycling (Salati et al., 1979; Gat and Matsui, 1991) or air mass origin (Tian et al., 2001). To draw inferences about these lower tropospheric processes, many studies have so far relied on the isotopic composition of precipitation (e.g., Salati et al., 1979; Gat and Matsui, 1991; Tian et al., 2001). However, precipitation is strongly affected by post-condensation processes that blur the original vapor signal (Stewart, 1975; Lee et al., 2008; Risi et al., 2008). It is also spatially sparse and discontinuous in time as it relies on rainy days. The SCIAMACHY instrument onboard the European research satellite ENVISAT was the first instrument to provide global retrievals of water isotopes with high sensitivity near the ground (Frankenberg et al., 2009). Such retrievals open

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the possibility of exploiting the potential of water isotopes to better understand the lower tropospheric water budget, such as the role of continental recycling or convection in this budget (Risi et al., 2010). Owing to instrumental degradation, the current data-record of SCIAMACHY HDO so far only covers the years 2003 through 2005 and connection to the entire ENVISAT satellite was irreparably lost in April 2012.

Here, we retrieve the column averaged deuterium depletion of atmospheric water vapor using the Japanese Greenhouse gases Observing Satellite (GOSAT, Hamazaki et al., 2005; Kuze et al., 2009), which was launched on 23 January 2009 into a sun-synchronous orbit with a local overpass time of 13:00. ≈ 10 000 soundings with 82 km^2 circular spatial footprints are recorded daily, repeating a regularly spaced global footprint grid every 3 days. Spectra are recorded by the TANSO Fourier Transform Spectrometer (FTS) onboard GOSAT. They enable independent retrievals of the total column amount of water vapor H_2O and its heavy isotope HDO in the 1.56 µm spectral region. This potential for GOSAT has so far not been exploited. We will discuss the retrieval setup in Sect. 2, validate and bias-correct the retrievals against ground-based observations in Sect. 3 and show global results and first comparisons with SCIAMACHY in Sect. 4.

2 HDO/H_2O retrieval setup from GOSAT

The column-averaged HDO abundance is often described in δ-notation, relative to standard mean ocean water (SMOW):

$$\overline{\delta D} = 1000‰ \cdot \left(\frac{\mathrm{VCD(HDO)/VCD(H_2O)}}{R_s} - 1 \right),$$

where VCD(HDO) and VCD(H_2O) denote the vertical column densities of HDO and H_2O, respectively. R_s ($= 3.1152 \times 10^{-4}$) is the ratio of HDO and H_2O for SMOW. VCD(H_2O) represents the vertically integrated total water vapor amount and is directly

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proportional to total precipitable water, a term more commonly used in hydrological sciences.

Our basic retrieval approach for $\overline{\delta D}$ largely follows retrievals from SCIAMACHY (e.g., Frankenberg et al., 2005a, 2008, 2009) using the IMAP-DOAS (Iterative Maximum a Posteriori – Differential Optical Absorption Spectroscopy) algorithm (Frankenberg et al., 2005b) with instrument specific adaptions and ECMWF meteorological data for pressure, temperature and a priori humidity profiles. CO_2 is the only interfering species and the disk-integrated solar line-list is adapted from the full-physics CO_2 retrievals used for GOSAT (originally developed for TCCON retrievals). The main difference with respect to the original IMAP-code is that we fit the spectra directly without taking the logarithm (however, as we use an iterative solver, the results are virtually identical). The continuum baseline is fitted with a 2nd order polynomial.

For the HDO a priori profile, we use a simplistic formulation, scaling the H_2O ECMWF prior profile with a pressure-dependent scaling factor, linearly varying from 0.9 at the surface to 0.5 at 50 hPa (i.e., a prior δD of -100 ‰ close to the surface and -500 ‰ in the stratosphere). In the state vector (both for HDO and H_2O), we include 10 retrieval layers, which are equidistant in pressure. The a priori covariance (1σ) was chose to be 15 % for all layers but the lowest, where 1500 % as 1σ ensures that the retrieval is effectively unconstrained. HDO and H_2O are treated as independent species without any side-constraints (besides the similarity in the prior profile) imposed on the HDO–H_2O functional relationship in the a priori covariance matrix. For the retrieval of $\overline{\delta D}$ we use nadir radiance spectra measured in the short-wave infrared, viz. in the spectral range around 6400 cm^{-1} (1.56 µm). The high spectral resolution of the TANSO FTS (2.5 cm maximum path difference resulting in 0.4 cm^{-1} unapodized spectral resolution) allows to retrieve weak HDO and H_2O lines in the aforementioned spectral range. Similar to retrievals of greenhouse gases in the near-infrared, the retrieval of profiles is not easily feasible due to low degrees of freedom and sensitivity to atmospheric scattering. Hence, we focus on retrieved total column amounts, which are more robust estimates

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in the near infrared. An exemplary spectral fit using data near Lamont (Oklahoma) is shown in Fig. 1.

In the spectral fit, the weak CO_2 band around $6340\,\mathrm{cm}^{-1}$ is included as it partially overlaps with HDO and H_2O lines. Even though spectral residuals (differences between modeled and measured radiances) are gaussian and devoid of outliers, the reduced χ^2 value is significantly higher than 1, mostly caused by low frequency variations in the continuum (see upper panel). The Jacobians with respect to total column changes in HDO and H_2O can be seen in the lower panel. As for spectroscopic parameters, we use CO_2 absorption coefficient tables (including line-mixing effects) generated for the ACOS (Atmospheric CO_2 Observations from Space) and Orbiting Carbon Observatory (OCO-2) projects (Thompson et al., 2012). HDO and H_2O cross sections are calculated based on the line-list used for TCCON (Total Carbon Column Observing Network, Wunch et al., 2011a) using pure Voigt line-shapes. The TCCON H_2O and HDO linelist contains the Toth (2005) and Jenouvrier et al. (2007) lines, with several additional empirically determined lines that have subsequently been assigned ground-state energies by Iouli Gordon (personal communication, 2010). All cross sections are pre-calculated as on-line calculations are computationally expensive. As rigid treatment of water self-broadening is not easily feasible, we use of an effective pressure $p_{\mathrm{eff}} = p_{\mathrm{ECMWF}}(1 + 4\mathrm{VMR}(H_2O))$, where VMR denotes volume mixing ratio and where we assume a ratio of the self to air-broadening coefficient of about 5. Under this assumption, the calculated line-shape is identical with one using self and air broadening parameters separately (which would, however, require one more dimension in the cross section lookup-tables, see Appendix A for the derivation of the effective pressure).

2.1 Quality filtering

We filter all retrievals based on a set of quality criteria, similar to O'Dell et al. (2012):

- $\chi^2 < 3$
- standard deviation of residuum $< 3 \times 10^{-9}\,\mathrm{W\,cm^{-1}\,sr^{-1}\,cm^{-1}}$

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- relative error in retrieved HDO column < 15 %
- passed simple cloud filter (fitted O_2 column amount > 90 % of ECMWF O_2 column amount)
- fitted H_2O column > 70 % of ECMWF prior
- $0.96 < CO_2$ ratio < 1.04
- $0.8 < H_2O$ ratio < 1.2

The CO_2 and H_2O ratios are from IMAP-DOAS retrievals using the weak and strong CO_2 bands. These retrievals have been performed under a non-scattering assumption and any strong deviation from this hypothesis leads to a divergence in retrieved abundances in the two bands. We found them to be particularly valuable in detecting strongly scattering scenes, including the detection of low-level clouds that can impact the retrieval accuracy.

2.2 Bias correction

Systematic errors in spectroscopy and instrumental effects can bias both the H_2O and HDO vertical column densities. Errors in line-strengths typically result in constant multiplicative biases while errors in line-shape (e.g., pressure broadening) can create biases which depend on both viewing geometry (mostly airmass) and total H_2O column amount as these determine the degree of saturation in Nadir-looking short-wave spectra. Constant multiplicative biases in the respective column densities will lead to a shift in $\overline{\delta D}$ and are not too worrisome as the variability in $\overline{\delta D}$ is unchanged and overall shifts are easy to calibrate out. Offsets in the retrieved column densities, however, can result in shifts that actually depend on the total amount of the retrieved columns. To investigate whether offsets are apparent in retrieved H_2O and HDO column amounts, we extracted all land-only retrievals south of 60° S where the a priori ECMWF column amount was below 8×10^{21} molecm^{-2}, i.e., a very dry atmosphere. This ensures a good

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fit of the intercept without a wet atmosphere dominating the slope fit, hence also the intercept. We then determined the offset by a least squares fit to a first order polynomial, based on the ECMWF and retrieved column densities.

Results are shown in Fig. 2. We observe a significant negative offset for HDO and a small positive offset for H_2O. A bias corrected $\overline{\delta D'}$ reads

$$\overline{\delta D'} = 1000\,‰ \cdot \left(\frac{c_1 \cdot \mathrm{VCD(HDO)} + 1.4 \times 10^{21}}{c_2 \cdot \mathrm{VCD(H_2O)} - 4.6 \times 10^{20}} \frac{1}{R_s} - 1 \right),$$

with potential multiplicative errors c_i in both vertical columns (caused by errors in line intensity and not quantified in this study). The negative offset in HDO would, if uncorrected, result in unphysical $\overline{\delta D}$ values and also lead to depletions approaching $-1000\,‰$ for column densities around 5×10^{21} molecm^{-2}. In other words, the slope in a Rayleigh curve ($\overline{\delta D}$ vs. H_2O) would be biased too steep, potentially affecting the interpretation of the results. We have neither found the root cause of the offset bias nor investigated the impact of erroneous broadening coefficients, which can lead to similar bias structures. Further complications may arise from the fact that both of these error terms can depend on the observed airmass, i.e., on season and latitude. However, the validation exercise in the following section will provide confidence that our simple bias correction yields very good agreement with ground-based observations over Lamont, Oklahoma.

3 Validation against up-looking FTS over Lamont, Oklahoma

For this proof of concept study, we chose a single TCCON station to validate GOSAT retrievals. For GOSAT satellite validation of greenhouse gases, e.g., Wunch et al. (2011b); Butz et al. (2011); Parker et al. (2011); Morino et al. (2011), Lamont had by far the largest number of coincidences, hence our choice to focus on this particular station. H_2O column amounts are validated against independent sonde measurements

(Wunch et al., 2010) but HDO results from TCCON itself are so far unvalidated. Retrieval windows for all datasets used in this study are listed in Tables 1–2. For GOSAT and TCCON, there is a strong overlap of the retrieval windows in the 6300–6400 cm^{-1} range.

We use the official TCCON GFIT algorithm to retrieve column amounts from high resolution up-looking near-infrared spectra. The GFIT retrieval scales an a priori profile, preserving its original shape. The H_2O a priori profile is interpolated from NCEP 6-hourly data to the latitude, longitude, date, and local solar noon time at the site. The HDO a priori profile is generated from the NCEP H_2O profile using an empirically-derived isotopic fractionation equation of $HDO = H_2O_{VMR}0.16(8.0 + \log(H_2O_{VMR}))$. At the tropopause ($H_2O_{VMR} = 3 \times 10^{-6}$) this equation gives $HDO/H_2O = 0.4$, whereas in the humid lower troposphere ($H_2O_{VMR} = 1 \times 10^{-2}$) the equation gives $HDO/H_2O = 0.96$.

Owing to the overlap in retrieval windows, column averaging kernels for HDO are very similar for TCCON and GOSAT (see Fig. 3). Averaging kernels for H_2O should ideally have little impact on retrieved columns as the a priori profile (NCEP for TCCON and ECMWF for GOSAT) is relatively close to the truth as multiple sonde measurements per day over Lamont are assimilated into the numerical weather forecast fields. For TCCON and GOSAT H_2O retrievals, their respective averaging kernels are substantially different. For TCCON, the column averaging kernel resembles the one for HDO with increasing sensitivity at lower pressures. This is mainly related to the fact that very weak lines are fitted in a column scaling retrieval. For GOSAT, the H_2O kernels are close to unity throughout the column while the HDO kernel is very close to TCCON.

Figure 4 shows a time-series of retrieved HDO (scaled by R_s) and H_2O column densities from GOSAT and the Lamont TCCON station with overlap from June 2009 through September 2011. Both columns are not bias corrected as it would hardly make a difference at this scale. Even though water vapor is highly variable and the coincidence criterion (±3°) is not very stringent, the overall seasonal cycle shape as well as the inter-annual variability are consistent. The measurements show peaks in mid-summer and overall higher column amounts in 2010 than in 2009 or 2011. Also the distinct

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summer peaks in 2010 and 2011 as well as the flat plateau for three consecutive months in 2009 are well reproduced. Values span a large dynamic range from about 0.1 % column averaged mixing ratio in winter to more than 0.6 % in summer (individual retrievals can approach 1 %).

Figure 5 shows a scatterplot of (not bias-corrected) GOSAT vs. ECMWF H_2O vertical columns using all individual retrievals over Lamont (≈ 1400 soundings). The retrievals are well correlated ($r^2 = 0.96$) albeit with a slope significantly smaller than unity, suggesting that H_2O is low-biased by about 10 % (resulting in a 100 ‰ high bias in $\overline{\delta D'}$ caused by H_2O; any additional errors in the HDO line-strength are difficult to quantify).

Figure 6 shows the time-series of $\overline{\delta D}$ monthly means (and bias corrected $\overline{\delta D'}$). It is obvious that the raw retrievals (owing to the offset) lead to a depletion in winter that is too strong while the bias corrected $\overline{\delta D'}$ exhibits similar magnitudes compared to TCCON. The overall shape of the seasonal cycle is extremely well reproduced in 2009 and early 2010, even showing unique month-to-month variability such as in October to November 2009 (with a sudden increase in $\overline{\delta D}$ even though the columnar water amount decreased). In the second half of 2010 and early 2011, the correlation seems to decrease somewhat with GOSAT showing a distinct single minimum in the winter of 2010/2011. However, potential sampling biases (due to the large coincidence criteria) can also result in mismatches between the satellite and the ground-based FTS. Also, both datasets exhibit an overall high-bias as depletions around −50–0 ‰ in summer are unphysical over Lamont. Hence, we focus instead on variability rather than accuracy of absolute values.

Looking at the overall correlation between GOSAT and TCCON, we find a correlation coefficient r^2 of 0.79 and a slope of the linear fit of 0.98. Figure 7 shows the linear fit to the monthly averages. The raw retrievals are still very well correlated with TCCON but show a slope significantly larger than unity (i.e., too steep). The good correlation and slope close to unity provides confidence in the GOSAT retrievals and indicates that accurate water isotope retrievals in the short-wave infrared are possible using GOSAT. We acknowledge that HDO from TCCON is currently not yet validated itself against

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independent datasets and that more rigorous validation work, such as in Schneider et al. (2010), both on the TCCON and GOSAT side, will be necessary on top of more sensitivity studies related to the retrieval setup as well as choice of spectroscopic parameters.

4 Intercomparisons with SCIAMACHY

SCIAMACHY is currently the only independent satellite dataset we can directly compare with as it also measures in the short-wave infrared (hence has a similar sensitivity). Unfortunately, currently available SCIAMACHY retrievals do not coincide in time with GOSAT as detector degradation makes SCIAMACHY retrievals after 2005 complicated. An extension of the dataset is planned but so far, we can only compare the two datasets regarding the spatial distribution of $\overline{\delta D}$ at seasonal time-scales. For this particular comparison, we use recently improved SCIAMACHY retrievals from Scheepmaker et al. (2012).

Figure 8 shows global averages for December–February (DJF), March–May (MAM), June–August (JJA) and September–November (SON). For GOSAT, we relaxed the filter criteria (esp. the CO_2 and H_2O ratio) to achieve high coverage in the tropics but most regions are hardly affected by this relaxation. One can see that the GOSAT glint viewing geometry over subtropical oceans results in a much higher data-yield. Over the oceans at higher latitudes, GOSAT takes regular Nadir observations and retrievals are so far only possible over low cloud layers having passed the simple filter (similar to SCIAMACHY which does not have a dedicated glint mode).

Overall, the spatial patterns as well as the seasonal variations are very similar but a different value range for SCIAMACHY was chosen as δD variability is somewhat lower in SCIAMACHY. This manuscript is of a technical nature but some aspects of the global distribution are worth discussing here: in boreal summer, highest $\overline{\delta D}$ (larger than both over the oceans and tropical South America) are found in tropical Africa. This is most likely related to a higher degree of continental recycling over Africa (Brubaker

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et al., 1993) because transpiration is a non-fractionating process, which can result in lower atmospheric depletions than over oceans. Other aspects of the distribution and its application in studies of hydrological cycles are extensively discussed in, e.g., Berkelhammer et al. (2011); Lee et al. (2009); Risi et al. (2012a,b); Lee et al. (2012).

Also noteworthy from a more technical viewpoint is the fact that GOSAT retrievals are very reliable over the oceans using the glint viewing geometry and also over land over some snow and ice areas such as Greenland. Both snow and ice have much lower surface albedos in the 2.3 µm range, making SCIAMACHY retrievals over these surface types problematic.

The lower variability of SCIAMACHY is apparent in Fig. 9: while correlation coefficients (r^2) of seasonal grid box averages vary between 0.65 in SON and 0.83 in JJA, the slopes vary between 1.20 and 1.46, showing that both datasets are strongly correlated but show a somewhat different variability in $\overline{\delta D}$. Without the bias correction already applied to the GOSAT data, this discrepancy would increase by an additional 25 %. One prime candidate for the discrepancies with SCIAMACHY is the averaging kernel for HDO for both GOSAT and TCCON. The column averaging kernels for HDO can well exceed unity while they are close to unity for SCIAMACHY. This can amplify both the latitudinal gradients as well as the seasonal amplitude in both GOSAT and TCCON (which compare well with each other as averaging kernels are similar) but not SCIAMACHY.

Despite the need for further research, the comparison with SCIAMACHY has shown that both datasets are well correlated even though they use entirely independent spectrometers and spectral regions. Apart from the aforementioned averaging kernels, spectroscopy, detector artifacts, differences in cloud filtering as well as spatial and temporal mismatches can all be causes for the current discrepancies. More validation using a consolidated set of ground-based observations will be necessary to rigorously evaluate and homogenize both data-products. Also, model information on HDO profiles to estimate the impact of the column averaging kernels will be necessary to quantify this impact.

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5 Conclusions

We have retrieved HDO and H_2O vertical column densities using short-wave infrared spectra from the Japanese GOSAT satellite. Column averaged deuterium depletions $\overline{\delta D}$ of atmospheric water vapour are retrieved with a precision that allows interpretation of single measurements (20–40 ‰). The enhanced precision, application of a different fitting window and small time-overlap is complementary to previous results from the SCIAMACHY instrument, which ceased operations in April 2012 and used the 2.3 µm range for HDO/H_2O retrievals. We compared GOSAT results against observations from the ground-based up looking Fourier Transform Spectrometer site in Lamont (Oklahoma) and find a very good agreement in the timing and amplitude of the $\overline{\delta D}$ seasonal cycle. Seasonal averages on the global scale also compare very well with the SCIAMACHY instrument, albeit with higher variability observed with GOSAT (potentially caused by differences in vertical sensitivity). While more sensitivity studies and validation exercises are warranted, we show that global retrievals of the composition of water vapour isotopologues from GOSAT are feasible and can provide a new benchmark for studies related to the hydrological cycle.

Appendix A

Derivation of effective pressure to include self-broadening effects

Under the assumption that the H_2O self-broadening coefficient is about 5 times larger than the air-broadening coefficient, the effective broadening coefficient in air (with H_2O) reads:

$$\gamma = \sum \left(\gamma_{n_i} \mathrm{VMR}(n_i)\right) \tag{A1}$$

$$\approx \gamma_{\mathrm{air}}(1 - \mathrm{VMR}(H_2O)) + \gamma_{H_2O}\mathrm{VMR}(H_2O) \tag{A2}$$

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$$= \gamma_{air}(1 - VMR(H_2O)) + 5\gamma_{air}VMR(H_2O) \quad (A3)$$
$$= \gamma_{air}(1 + 4VMR(H_2O)) \quad (A4)$$

Since the actual width of the line is the product of γ with air pressure, a multiplication of the pressure with $(1+4VMR(H_2O)$ and subsequent use of just γ_{air} leads to a good approximation of the final line-shape without the need to compute the self-broadening part explicitly.

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Table 1. Retrieval windows for HDO and H_2O used for GOSAT and SCIAMACHY.

GOSAT (cm^{-1})	SCIAMACHY (cm^{-1})
6310–6440	4212–4248

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Table 2. Retrieval windows for HDO and H_2O used for TCCON (center frequencies ± range, interfering species in brackets).

TCCON H_2O (cm^{-1})		TCCON HDO (cm^{-1})	
4565.20 ± 1.250	(H_2O CH_4 CO_2)	4054.60 ± 3.30	(H_2O CH_4)
4571.75 ± 1.250	(H_2O CH_4 CO_2)	4116.10 ± 8.00	(H_2O CH_4)
4576.85 ± 0.950	(H_2O CH_4)	4212.45 ± 1.90	(H_2O CH_4)
4611.05 ± 1.100	(H_2O CH_4)	4232.50 ± 11.00	(H_2O CH_4 CO)
4622.00 ± 1.150	(H_2O CO_2)	6330.05 ± 45.50	(H_2O CO_2)
4699.35 ± 2.000	(H_2O CO_2 N_2O)	6377.40 ± 50.20	(H_2O CO_2)
6076.90 ± 1.975	(H_2O CH_4 CO_2 HDO)		
6099.35 ± 0.475	(H_2O CO_2 HDO)		
6125.85 ± 0.725	(H_2O CH_4 CO_2 HDO)		
6177.30 ± 0.415	(H_2O CH_4 CO_2 HDO)		
6255.95 ± 1.800	(H_2O CO_2 HDO)		
6301.35 ± 3.950	(H_2O CO_2 HDO)		
6392.45 ± 1.550	(H_2O HDO)		
6401.15 ± 1.150	(H_2O HDO CO_2)		
6469.60 ± 1.750	(H_2O HDO CO_2)		s

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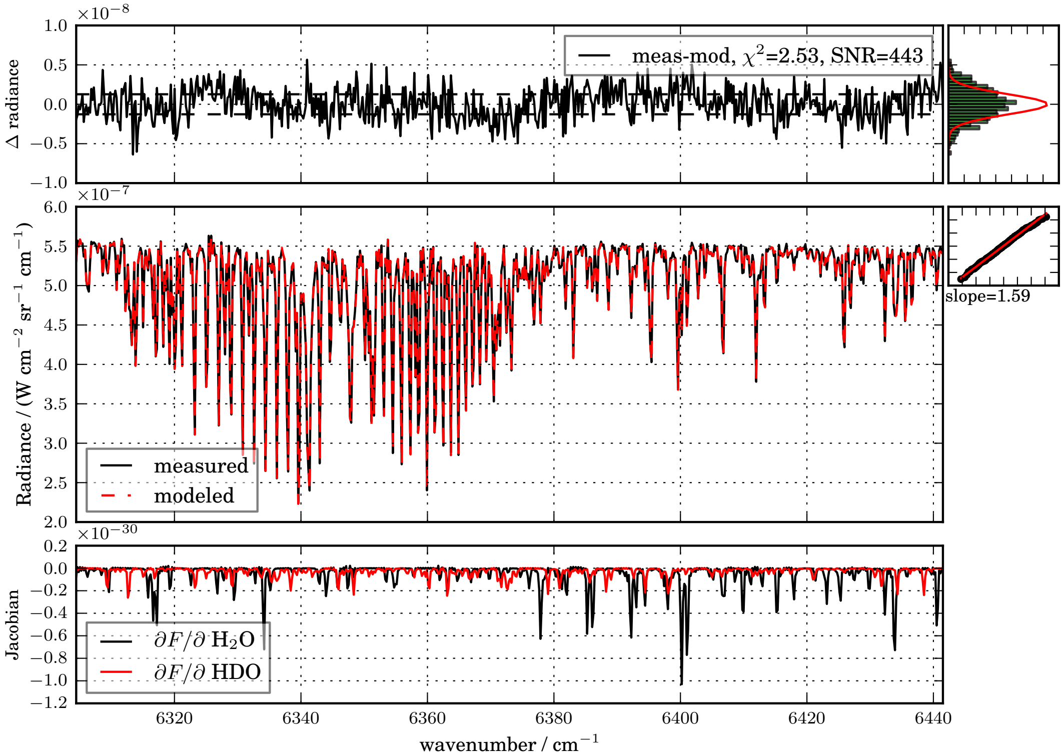

Fig. 1. Center: HDO and H_2O example fit using GOSAT spectra over Lamont, Oklahoma (black = measured, red = modeled). The upper panel shows spectral residuals (1σ noise levels indicated by dashed lines). The upper rightmost panel shows the probability density function of observed residuals (black) and the expected distribution based on GOSAT noise estimates (red). The lower rightmost panel shows a QQ plot (quantile-quantile plot) showing that the distribution of residuals are Gaussian. The lowest panel shows Jacobians for the HDO and H_2O column amount.

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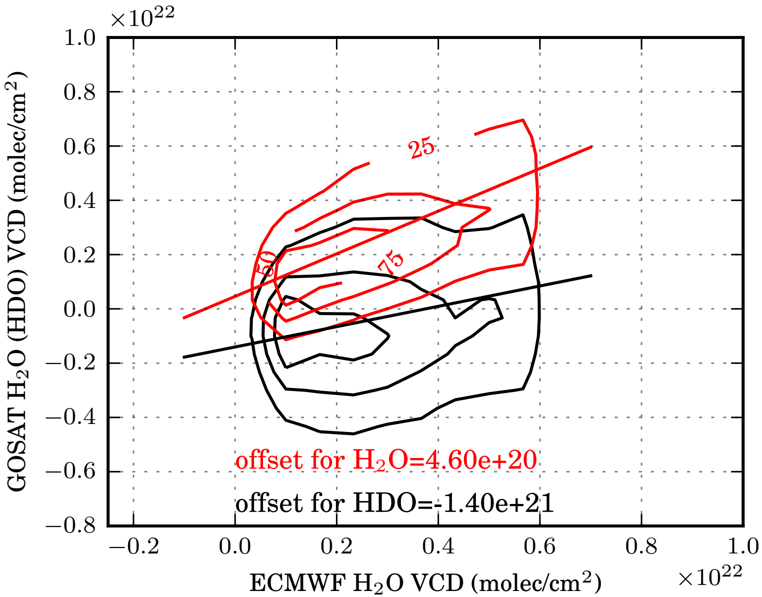

Fig. 2. Frequency distribution and linear fit of retrievals and ECMWF estimates over very dry regions (mostly Antarctica coincidences chosen here). Contour lines show 25, 50 and 75 percentile distributions. Small offset errors in both HDO and H_2O column estimates can be observed, and fitted offsets are used in the subsequent bias correction.

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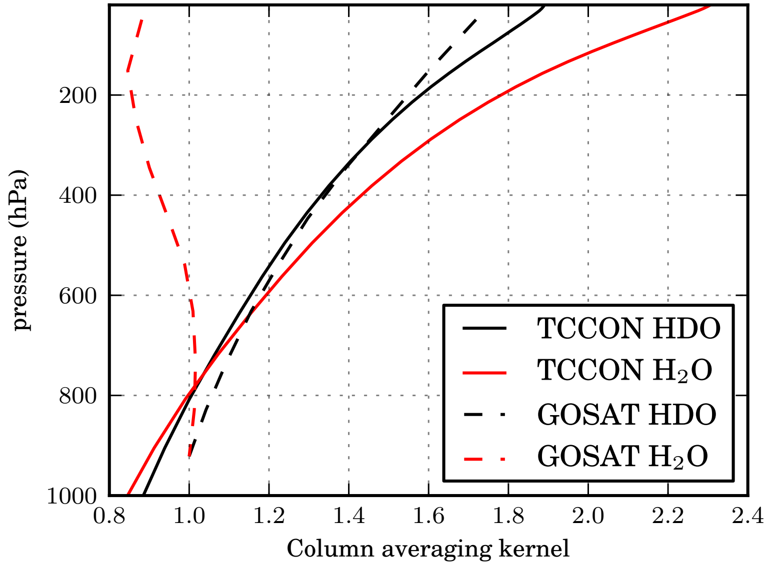

Fig. 3. Typical TCCON and GOSAT column averaging kernels for H_2O and HDO.

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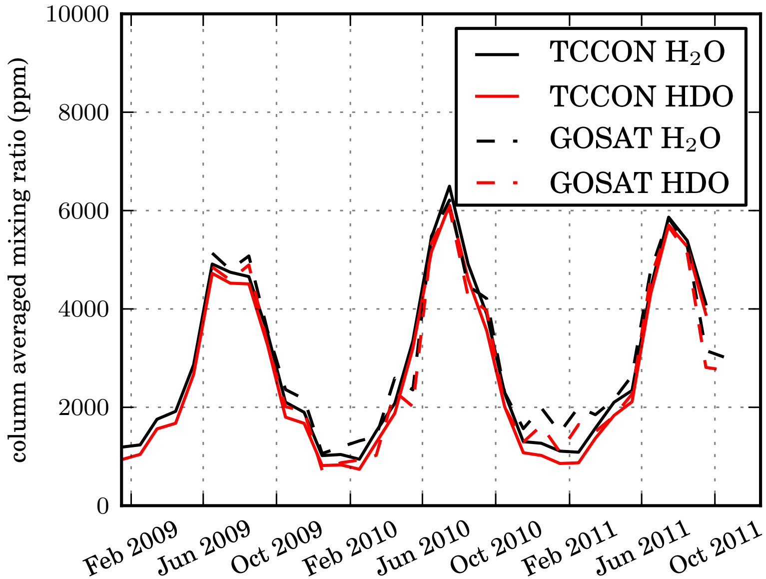

Fig. 4. Comparison of monthly HDO and H_2O column amounts over the Lamont (Oklahoma) TCCON station (GOSAT coincidences within ±3° latitude and longitude).

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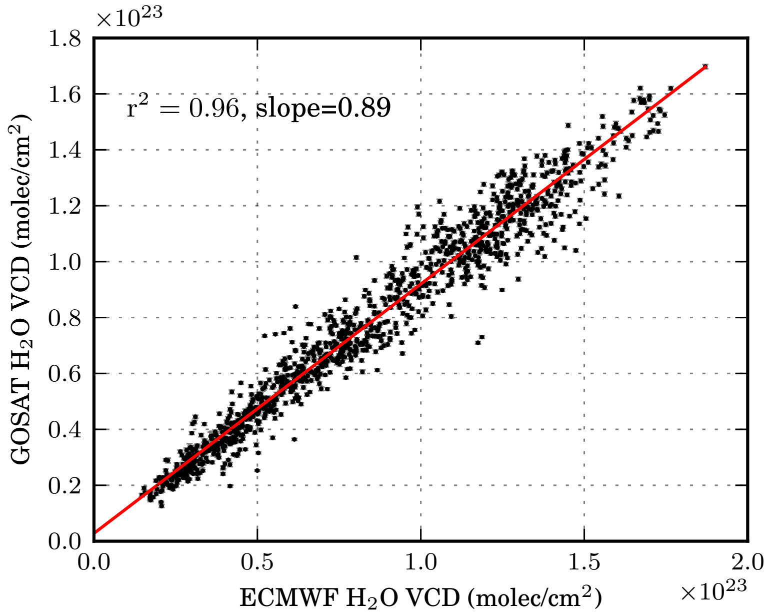

Fig. 5. Comparison of single soundings of GOSAT H_2O with ECMWF analysis data (used as prior in the retrieval but not constrained in the retrieval).

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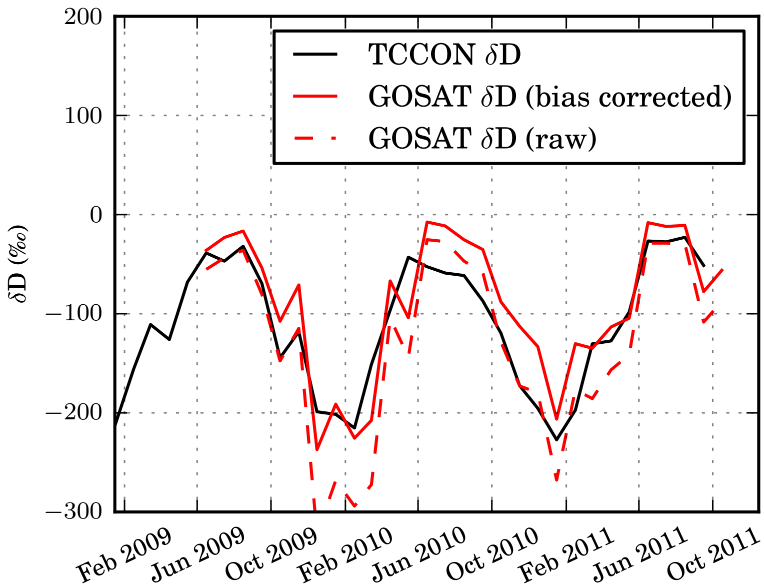

Fig. 6. Comparison of monthly δD over the Lamont (Oklahoma) TCCON station (GOSAT coincidences within ±3° latitude and longitude).

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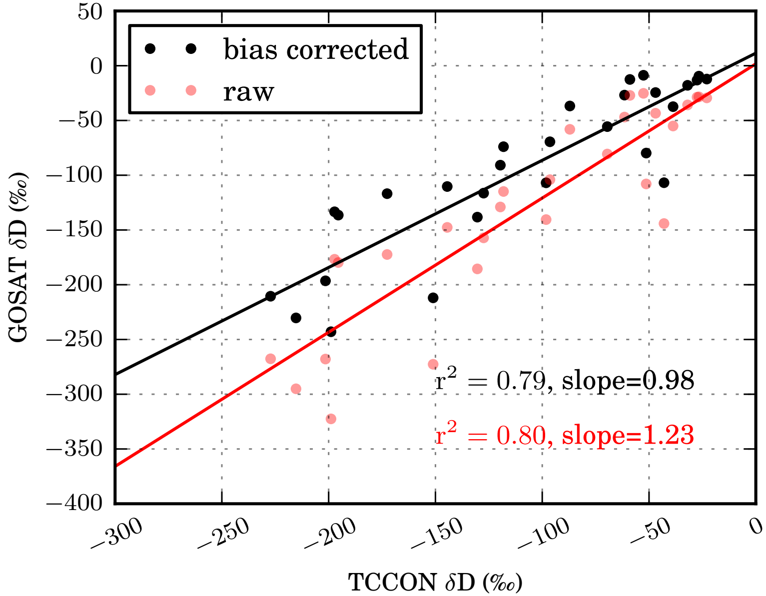

Fig. 7. Scatterplot and linear fit of monthly $\overline{\delta D}$ over the Lamont (Oklahoma) TCCON station (TCCON vs. GOSAT).

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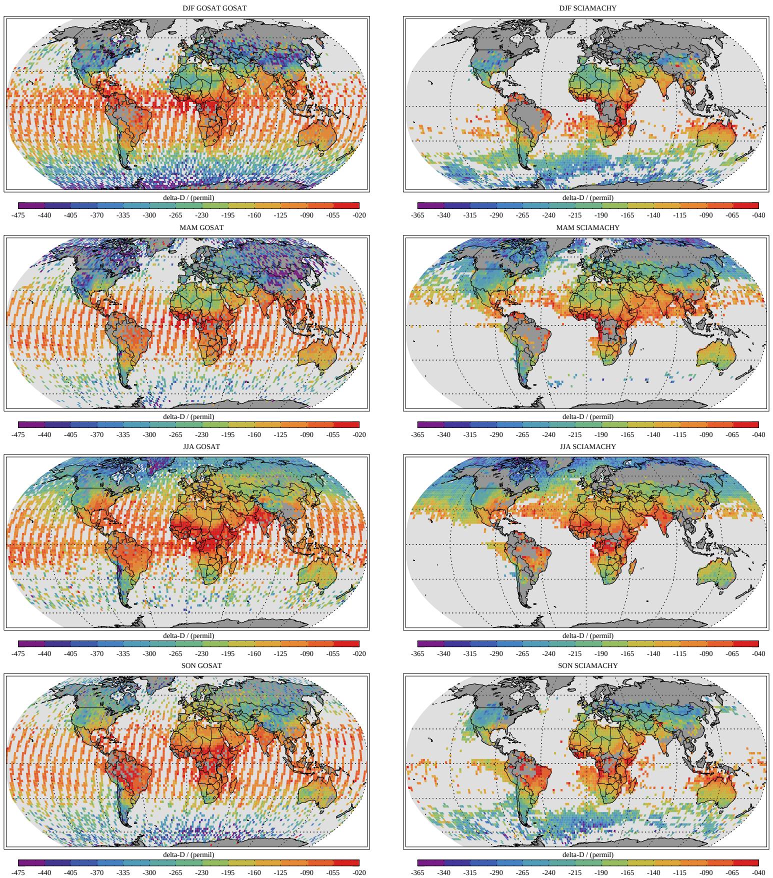

Fig. 8. Spatial distribution of seasonal 2 × 2 degree grid box averages of $\overline{\delta D'}$ for GOSAT (left panels, 2009–2011) and SCIAMACHY (right panels, 2003–2005).

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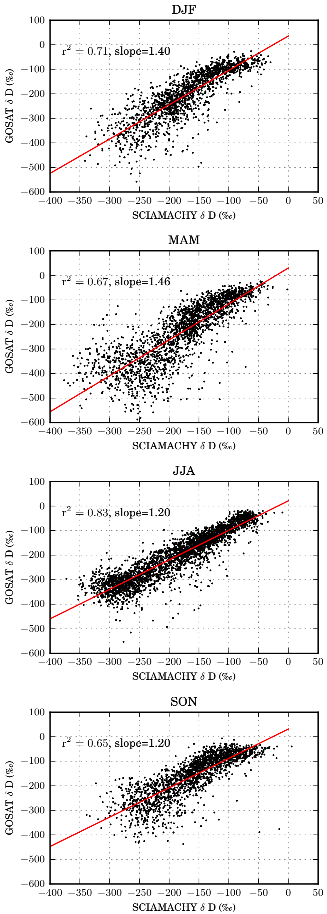

Fig. 9. Scatterplots of SCIAMACHY (2003–2005) and GOSAT (2009–2011) seasonal 2 × 2 degree grid box averages.

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