

Intercomparison of arctic XH₂O observations from three ground-based FTIR networks and application for satellite validation

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15 **Abstract.**

In this paper, we compare column-averaged dry-air mole fractions of water vapor (XH₂O) retrievals from COCCON (Collaborative Carbon Column Observing Network) with retrievals from two co-located high-resolution FTIR (Fourier transform infrared) spectrometers as references at two boreal sites, Kiruna, Sweden and Sodankylä, Finland from March 6 2017 to September 20 2019. In the framework of the NDACC (Network for the Detection of Atmospheric Composition Change) an FTIR spectrometer is operated in Kiruna. The H₂O product derived from these observations has been generated with the MUSICA (MULTi-platform remote Sensing of Isotopologues for investigating the Cycle of Atmospheric water) processor. In Sodankylä, a TCCON (Total Carbon Column Observing Network) spectrometer is operated, and the official XH₂O data as provided by TCCON are used for this study. The datasets are in good overall agreement, with COCCON data showing a wet bias of (49.20 ± 58.61) ppm ((3.33 ± 3.37) %, $R^2=0.9992$) compared to MUSICA NDACC and (56.32 ± 45.63) ppm ((3.44 ± 1.77) %, $R^2=0.9997$) compared to TCCON.

25 Furthermore, the a priori H₂O VMR (volume mixing ratio) profiles (MAP) used as a priori in the TCCON retrievals (also adopted for COCCON retrievals) are evaluated with respect to radiosonde (Vaisala RS41) profiles at Sodankylä. The MAP and radiosonde profiles show similar shapes and a good linear correlation of integrated XH₂O, indicating that MAP is a reasonable approximation for the true atmospheric state and an appropriate choice for the scaling retrieval methods as applied by COCCON and TCCON. COCCON shows a reduced dry bias (-14.96 %) in comparison to TCCON (-19.08 %) with respect to radiosonde XH₂O.

30 Finally, we investigate the quality of satellite data at high latitudes. For this purpose, the COCCON XH₂O is compared with retrievals from the Infrared Atmospheric Sounding Interferometer (IASI) generated with the MUSICA processor (MUSICA IASI) and with retrievals from the TROPOspheric Monitoring Instrument (TROPOMI). Both paired datasets show generally good agreement and similar correlations at the two sites. COCCON measures 4.64 % less XH₂O at Kiruna and 3.36 % at

Sodankylä with respect to MUSICA IASI, while COCCON measures 9.71 % more XH₂O at Kiruna and 7.75 % at Sodankylä compared with TROPOMI.

Our study supports the assumption that COCCON also delivers a well-characterized XH₂O data product. This emphasizes the approach of supplementing the TCCON network for satellite validation efforts. This is the first published study where
40 COCCON XH₂O is compared with MUSICA NDACC and TCCON retrievals, and for MUSICA IASI and TROPOMI validation.

1. Introduction

Water vapor (H₂O) is among the most abundant gases in the atmosphere and nearly 99 % of the water vapor exists in the troposphere. It has a residence time of about nine days in the atmosphere (Trenberth, 1998) and absorbs approximately 57 %
45 in the long-wave radiation and 72 % in the short-wave in clear skies (Kiehl and Trenberth, 1997). Due to its numerous absorption, atmospheric water vapor also acts as an important greenhouse gas (GHG). It plays a key role in the Earth's energy budget and the large-scale circulation, and thus the climate of our planet (Allan, 2012). Because the equilibrium water vapor pressure increases rapidly with temperature, the increasing atmospheric concentration of water vapor further amplifies warming due to its added radiative absorption (Soden et al., 2002). Therefore, assessing and quantifying atmospheric water
50 vapor is essential to constrain weather and climate models.

The distribution of water vapor in the atmosphere is characterized by very high spatial and temporal variability relevant to weather and climate (Vogelmann et al., 2015). Satellite-borne instruments have the advantage of global coverage but lack of vertical or long-term information (Dupuy et al., 2016). Additionally, satellite water vapor data contain inherent uncertainties and must be validated before use (Loew et al., 2017). On the other hand, independent ground-based remote sensing instruments
55 and in situ sensors do not give access to the global scale but can provide very accurate and long-term data, which can be used for satellite validation. Many studies have investigated water vapor comparisons among satellite and ground-based instruments (Schneider and Hase, 2011; Dupuy et al., 2016; Borger et al., 2018; Trieu et al., 2019), but there are only few studies that focus on the Arctic region (Palm et al., 2010; Buehler et al., 2012; Alraddawi et al., 2018).

In this work, we present a comparison of column-averaged dry-air mole fractions of water vapor (XH₂O) retrievals from
60 three ground-based networks, two space-borne satellites and vertical profiles from in situ radiosondes near Arctic region. This paper is organized as follows: Sect. 2 gives a description of the campaign sites and lists the details of the instruments. The datasets used in this study and coincidence criteria will be presented in Sect. 3. Results are discussed in Sect. 4 and 5, followed by conclusions in Sect. 6.

2. Ground-based and space-borne instrumentation

65 2.1 TCCON network

The Total Carbon Column Observing Network (TCCON) is a worldwide network of ground-based Fourier transform infrared (FTIR) spectrometers, measuring solar absorption spectra in the near infrared region. The TCCON network is designed to provide accurate and long-term time series of column-averaged dry-air mole fractions of greenhouse gases and other atmospheric constituents for carbon cycle studies and satellite validation (Wunch et al., 2011). The TCCON measurements
70 have very high precision due to the minimal effect from surface properties and aerosols (Wunch et al., 2017). The TCCON sites are distributed globally, but with higher density in Europe, Northern America and eastern Asia. Its costs and high demand for qualified personnel and infrastructure hinder its expansion. Remote sites or regions with high or low surface albedo, which are also interesting for satellite and model validation are generally poorly covered by the TCCON stations.

TCCON data are retrieved by the non-linear least-squares fitting algorithm (GFIT). The GFIT algorithm scales a priori
75 water vapor profiles from the National Centers for Environmental Prediction reanalysis data (<https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/reanalysis-1-reanalysis-2>) to obtain a best-fit synthetic spectrum for the measured spectrum (Wunch et al., 2011). Some retrieval information for TCCON and other products used in this study are listed in Table A 1.

2.2 COCCON network and FRM4GHG campaign

Recently, a cheaper, robust and portable ground-based FTIR spectrometer (EM27/SUN) has been developed by the Karlsruhe
80 Institute of Technology (KIT) in cooperation with the company Bruker (Gisi et al. (2012), Frey et al. (2015) and Hase et al. (2015, 2016)). The EM27/SUN instruments are characterized with good quality, robustness and reliability in several successful field campaigns (Frey et al., 2015; Klappenbach et al., 2015; Chen et al., 2016; Butz et al., 2017; Vogel et al., 2019; Sha et al., 2019; Tu et al., 2020; Jacobs et al., 2020) and their excellent level of performance opens up the chance of supporting the TCCON network. The spectrometers are commercially available since spring 2014 and today about 60 spectrometers are in
85 operation around the world. KIT initiated the COllaborative Carbon Column Observing Network (COCCON, <https://www.imk-asf.kit.edu/english/COCCON.php>) as a framework for proper operation of the EM27/SUN spectrometer (Frey et al., 2019) and for ensuring common standards for data analysis. Each COCCON spectrometer (including the spectrometers operated in Kiruna and Sodankylä as used in this study) is checked and calibrated at the calibration facility operated in Karlsruhe (using a TCCON spectrometer and the primary EM27/SUN spectrometer unit) before shipment to the
90 observation site. For the purpose of COCCON data processing, a preprocessing tool and the non-linear least-squares fitting algorithm PROFFAST have been created with the support of the European Space Agency (ESA) (projects COCCON-PROCEEDS and COCCON-PROCEEDS II). The EM27/SUN spectrometer offers a low spectral resolution of 0.5 cm^{-1} and consequently has little vertical resolution capability. Therefore, a simple least-squares fit performing a scaling retrieval of the a priori profile is generally appropriate and sufficient.

95 In this work, two COCCON instruments were operated at the Swedish Institute of Space Physics (IRF), Kiruna, Sweden
(67.84° N, 20.41° E, 419 m a.s.l.) and at the Finnish Meteorological Institute (FMI), Sodankylä, Finland (67.37° N, 26.63° E,
181 m a.s.l.) since March 2017. The COCCON measurements in Finland are made in the frame-work of the FRM4GHG
(Fiducial Reference Measurements for Ground-Based Infrared Greenhouse Gas Observations, <http://frm4ghg.aeronomie.be/>)
campaign, funded by ESA. This campaign aims at characterizing the performance of several low-cost and portable instruments
100 for performing GHG measurements simultaneously in comparison with the TCCON retrievals at FMI, Finland (Sha et al.,
2019). The dataset from this campaign will also serve for the TROPOspheric Monitoring Instrument (TROPOMI) validation
and the campaign provides a guideline for establishing portable low-resolution FTIR spectrometers for complementing the
TCCON network.

2.3 MUSICA NDACC products

105 The quality assessment study is also complemented by the MUSICA (MUlti-platform remote Sensing of Isotopologues for
investigating the Cycle of Atmospheric water) dataset, including ground-based remote sensing, space-based remote sensing
and in situ measurements (Schneider et al., 2012; Schneider et al., 2016). In this study, we focus on the first dataset.

Currently, there are 12 NDACC (Network for the Detection of Atmospheric Composition Change, <http://www.acd.ucar.edu/irwg/>, Kurylo and Zander, 2000; De Mazière et al., 2018) stations for which MUSICA NDACC
110 datasets were created (Barthlott et al., 2017). The MUSICA NDACC retrievals are made by fitting 9 different spectral
microwindows with water vapor signatures in the spectral region between 2655 and 3055 cm^{-1} using the PROFFIT retrieval
code (PROFile FIT, Hase et al. 2004). The retrieval consists of an optimal estimation of the vertical distribution of H_2O ,
together with the ratios of different water vapor isotopologues. For all the retrievals a constant unique a priori profile is used,
which is a global mean water vapor state, i.e. there is no variability in the a priori. This has the advantage that all detected
115 variability is induced by the observation, but at the cost that the a priori profile can be rather off from the actual atmospheric
state, which is a minor issue given the vertical sensitivity as revealed by the profile averaging kernels (Barthlott et al., 2017).
Here we use MUSICA NDACC from the NDACC data base and perform a simple bias correction. This correction consists in
adding $A*c$ to the original data, where A is the averaging kernel in logarithmic scale and c a profile vector with the entry -0.12
for all altitudes. This means that we consider a bias of +12 % in the original MUSICA H_2O data.

120 The PROFFIT code has been successfully used for many years in the ground-based FTIR community for evaluating high-
resolution solar absorption spectra (Hase et al., 2004; Schneider and Hase, 2011). NDACC enables monitoring the distribution
of a large variety of atmospheric trace gases in the mid-infrared region with Bruker HR120/5 FTIR spectrometers, including
water vapor at a very high precision (Schneider et al., 2006; Schneider and Hase, 2009; Schneider et al., 2010a). The Kiruna
NDACC observations are well representative for high latitudes and the MUSICA NDACC Kiruna data are available for the
125 whole period from 1996 to present (Blumenstock et al., 2006).

2.4 MUSICA IASI products

The Infrared Atmospheric Sounding Interferometer (IASI) is the primary payload carried on the EUMETSAT's MetOp series of polar-orbiting satellites (Clerbaux, 2009), which provides a near-global distribution of observations with high resolution and accuracy twice a day. There are currently three IASI instruments in operation, which were launched in 2006, 130 2012 and 2018, respectively. The primary intent of IASI is to provide information on atmospheric temperature and water vapor, although several additional trace gases are accessible in the spectra.

The MUSICA NDACC retrievals are based on the retrieval code PROFFIT while the MUSICA IASI retrievals are based on a nadir version of PROFFIT (Schneider and Hase, 2009). The retrieval uses a single broad spectral window between 1190 and 1400 cm^{-1} and consists of a simultaneous optimal estimation of the vertical distribution of H_2O , the ratio of different water 135 vapor isotopologues, N_2O , CH_4 , and HNO_3 . Atmospheric temperature is also fitted but constrained strongly to the EUMETSAT IASI Level 2 temperature product. For more details on the MUSICA IASI retrievals and the validation of the MUSICA IASI H_2O product please refer to Schneider et al. (2016) and Borger et al. (2018). The version presented here is an update as described by Borger et al. (2018) using a priori profiles for the gases under consideration, which depend on season and latitude. This dependency is determined from WACCM (Whole Atmosphere Community Climate Model) model simulations (a more 140 detailed description of the new MUSICA IASI retrieval version is currently in preparation for ESSD (Earth System Science Data)).

2.5 TROPOspheric Monitoring Instrument

The Tropospheric Monitoring Instrument (TROPOMI) is the single payload onboard the Sentinel-5 Precursor (S5P) satellite and was launched in October 2017 (Veefkind et al., 2012). It is a nadir-viewing grating spectrometer, covering the ultraviolet 145 to shortwave infrared (SWIR) band. The SWIR module on TROPOMI has a spectral range of 4190 – 4340 cm^{-1} , a spectral resolution of 0.45 cm^{-1} and an unprecedented spatial resolution of 7 km \times 7 km (5.5 km \times 7 km after August 2019). A study from Schneider et al. (2020) shows a good agreement between the corrected TCCON H_2O column and co-located TROPOMI H_2O column, with a mean bias of $(-0.2 \pm 3) \times 10^{21}$ molec. cm^{-2} ((1.1 ± 7.2) %).

2.6 In situ radiosonde

150 Atmospheric profiles are regularly measured by meteorological radiosondes. In January – March 2017 Vaisala RS92 radiosondes (Dirksen et al., 2014) were launched at Sodankylä. The radiosonde system was upgraded in March 2017 and since late March 2017 Vaisala RS41 radiosondes have been launched at 23:30 UTC and 11:30 UTC daily. During special observing periods additional radiosondes have been launched at 05:30 UTC and 17:30 UTC. The regular radiosondes at Sodankylä have been launched using an automated launching system by Vaisala Oy since early 2006 (Madonna et al., 2020). Vaisala RS41 155 radiosonde contributes to improvements in accuracy and data consistency and its specifications for combined measurement uncertainties are 0.3 $^{\circ}\text{C}$ for temperature below 16 km and 0.4 $^{\circ}\text{C}$ above, 4 % RH for relative humidity, 1.0 hPa for pressure

larger than 100 hPa and 10 m for geopotential height (<https://www.vaisala.com/sites/default/files/documents/RS-Comparison-White-Paper-B211317EN.pdf>).

3. Datasets used and coincidence criteria

160 3.1 Ground-based datasets

In the present study, all datasets are obtained during the period from 2017 to 2019. We used the MUSICA NDACC XH₂O data from Kiruna (Barthlott et al., 2017) and the latest version GGG2014 TCCON XH₂O data from Sodankylä (Kivi and Heikkinen, 2016; Kivi et al., 2017) as references.

The COCCON and TCCON XH₂O is computed as the ratio of the co-retrieved total column of O₂ to an assumed dry-air
165 mole fraction of O₂ equal to 0.2095 (Wunch et al., 2015):

$$XH_2O = \frac{TC_{H_2O}}{TC_{O_2}} \times 0.2095 \quad (1)$$

The total column of O₂ is not available from the NDACC network. Therefore, the XH₂O is calculated by dividing the total column of H₂O by the total column of dry air and the latter is computed from the surface pressure (P_s) recorded at a local weather station:

$$TC_{dryair} = \frac{P_s}{m_{dryair} \times g(\varphi)} - \frac{m_{H_2O}}{m_{dryair}} \times TC_{H_2O} \quad (2)$$

$$XH_2O = \frac{TC_{H_2O}}{TC_{dryair}} \quad (3)$$

where P_s is the surface pressure at Kiruna ground level, m_{dryair} and m_{H_2O} are the molecular masses of dry air ($\sim 28.96 \text{ g} \cdot \text{mol}^{-1}$) and water vapor ($\sim 18 \text{ g} \cdot \text{mol}^{-1}$), respectively, TC_{dryair} and TC_{H_2O} are the total column amount of dry air and water
170 vapor, and $g(\varphi)$ is the latitude-dependent surface acceleration due to gravity.

The co-located COCCON measurements from Kiruna and Sodankylä are coincident with NDACC and TCCON measurement with hourly mean, respectively. Due to the high measurement frequency, the TCCON and COCCON measurements offer opportunities for estimating the water vapor intraday variability. To reduce the residual uncertainties
175 introduced by air mass dependence, empirical corrections are applied by TCCON (Wunch et al., 2015) and COCCON. The solar zenith angle (SZA) range has been limited to 80°. This also reduces the collocation error with the satellite borne thermal nadir sounder IASI, whose typical nadir angle range is 0° – 48.3°.

3.2 Space-borne datasets

For space-borne data, a similar geophysical collocation criterion is used in this study as used in Schneider et al. (2020). The
180 MUSICA IASI and TROPOMI data are collected within a radius of 30 km of the COCCON sites in Kiruna and Sodankylä with an acceptance cone of 45° width in the FTIR viewing direction and all ground-based measurements acquired within 30

min of each satellite overpass (before or after). To reduce the altitude effect, the satellite data are filtered for ground pixels with altitudes between 350 and 500 m a.s.l. for Kiruna and 100 and 250 m a.s.l. for Sodankylä, respectively (Kiruna and Sodankylä stations are located at 420 and 189 m a.s.l., respectively). For the TROPOMI data we also applied additional filters for reducing the effects of clouds and high aerosol. The cloud cover is limited to 1 % for both the inner and outer field of view (Schneider et al., 2020). The soundings with high aerosol load are filtered out with a two-band methane filter, when the difference between the retrieved methane in weak and strong absorption is larger than 6 % (Scheepmaker et al., 2016; Hu et al., 2018).

It is noted that the seasonal variation of atmospheric water vapor is large; therefore, we report the bias and also relative bias (in percent) for one pair of XH₂O datasets. The relative bias is calculated as below:

$$Rel. bias = 2 \times \frac{X_{gas_A} - X_{gas_B}}{(X_{gas_A} + X_{gas_B})} \times 100 \% \quad (4)$$

3.3 Volume mixing ratio of H₂O derived from radiosonde measurements

The relative humidity (RH) measured by the in situ radiosondes is equivalent to the partial pressure of H₂O divided by the saturation vapor pressure of H₂O:

$$RH = \frac{P_{H_2O}}{e_s(T)} \times 100 \% \quad (5)$$

where P_{H₂O} is the partial pressure of H₂O, e_s(T) is the saturation vapor pressure which only depends on temperature. Here we use the empirical equation from Hyland and Wexler (1983) to present e_s:

$$e_s = \exp\left(\frac{-0.58002206 \times 10^4}{T} + 0.13914993 \times 10 - 0.48640239 \times 10^{-1} \times T + 0.41764768 \times 10^{-4} \times T^2 - 0.14452093 \times 10^{-7} \times T^3 + 0.65459673 \times 10 \times \log(T)\right) \quad (6)$$

where *T* denotes the temperature in Kelvin.

The volume mixing ratio (VMR) of H₂O (VMR_{H₂O}) is defined as the ratio of partial pressure of H₂O (P_{H₂O}) relative to the total pressure (*P*):

$$VMR_{H_2O} = \frac{P_{H_2O}}{P} \quad (7)$$

Combing Equations (5) – (7) allows the VMR of H₂O to be computed from radiosonde measurements of relative humidity, temperature and pressure:

$$VMR_{H_2O} = \frac{RH \times e_s(T)}{P} \quad (8)$$

where *RH* denotes the relative humidity, e_s denotes the saturation vapor pressure and *P* denotes the total pressure.

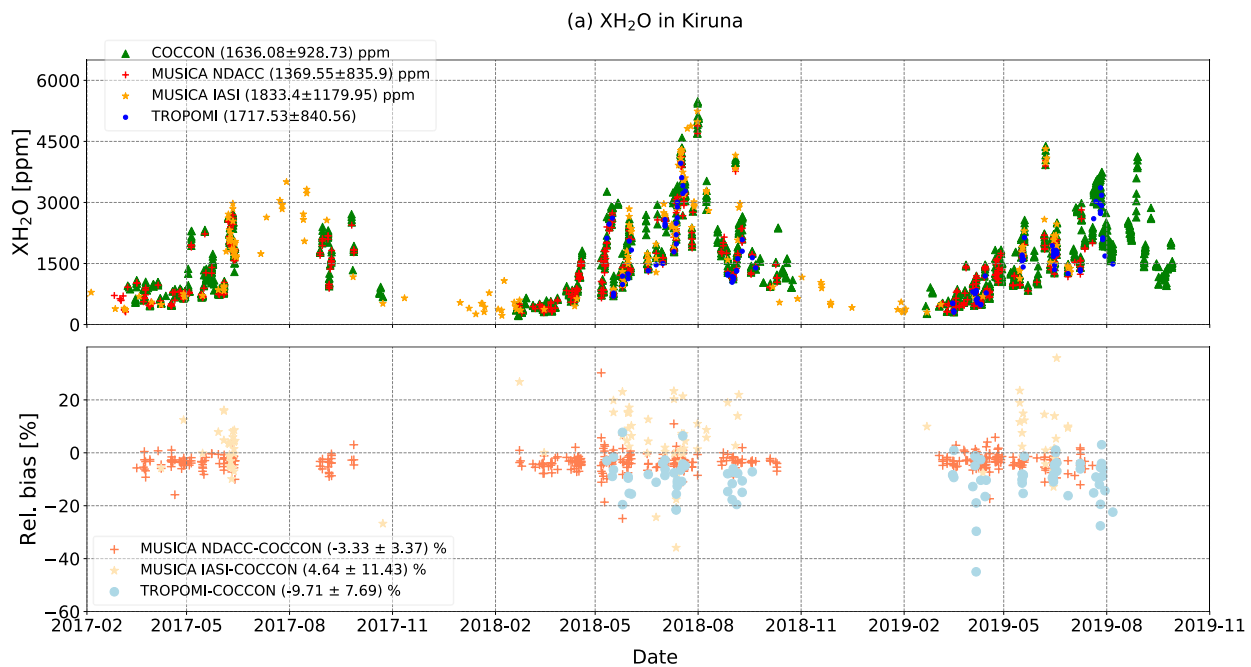
4. Comparison of Arctic COCCON XH₂O

We determine the precision by an intercomparison between COCCON and ground-based FTIR datasets. The XH₂O observed by the COCCON instruments at two sites is first compared with co-located ground-based MUSICA NDACC retrievals for Kiruna and with TCCON retrievals for Sodankylä, respectively. Furthermore, in situ radiosonde profiles at Sodankylä are used to investigate the a priori profile shape, and to evaluate TCCON and COCCON XH₂O data.

4.1 Seasonal variations of XH₂O

Time series of different datasets from 2017 (TROPOMI starting from 2018) to 2019 are depicted in Fig. 1 for Kiruna and Sodankylä. COCCON measurements observe seasonal variations of XH₂O similar to the NDACC and TCCON measurements at each site. Here, we use additionally IASI and TROPOMI in the comparison and these datasets will be further discussed in Section 5. Multiple gaps are existing in the ground-based FTIR datasets due to poor weather and high SZA condition, while the FTIR measurements are performed under clear sky condition or during breaks in cloud cover. The number of MUSICA NDACC data is lower than the number of COCCON measurements due to the longer measuring time for NDACC compared to that of COCCON spectra and due to the use of optical filters by NDACC, which are recorded in sequence. The MUSICA NDACC data analyses use measurements recorded with one out of 6 optical filters used in the NDACC measurements.

In general, there are higher amounts of atmospheric XH₂O in summer than in spring and winter. For Kiruna, the amounts of XH₂O reach up to ~4000 ppm in each August 2017 and 2019 and even up to ~5500 ppm in August 2018, while there is only ~600 ppm XH₂O in each early spring and winter. Specific humidity shows a strong positive correlation with temperature (Issac and Wijngaarden, 2012). Meanwhile, the higher precipitation in summer intensifies the higher atmospheric water vapor concentration. The evaporation from the snow-covered continent and frozen water surface is still much less, limiting the transport of water vapor into the atmosphere. This effect lasts until spring due to the slow warming of the surface (Wypych et al., 2018). The XH₂O concentration is slightly higher at Sodankylä than at Kiruna, especially in summer. This is because the Sodankylä site (181 m a.s.l) has a lower altitude than the Kiruna site (419 m a.s.l), associated with enhanced contributions of humid atmospheric layers near ground to XH₂O.



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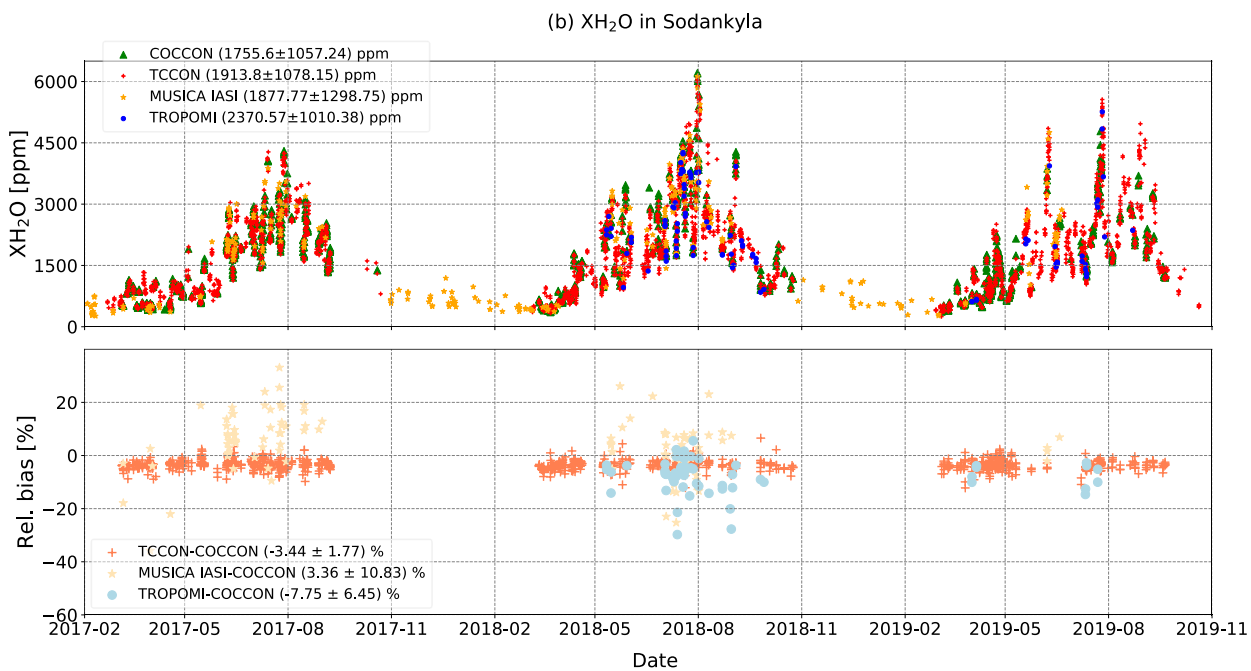
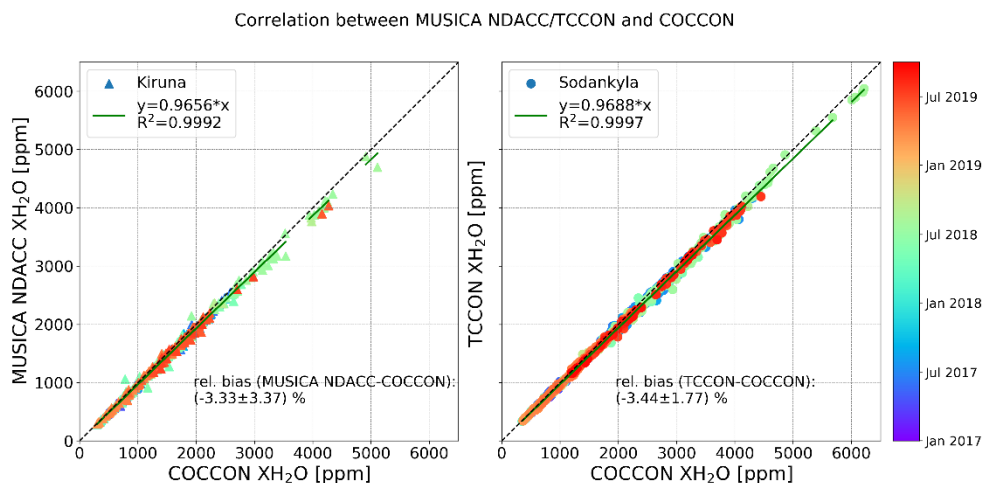


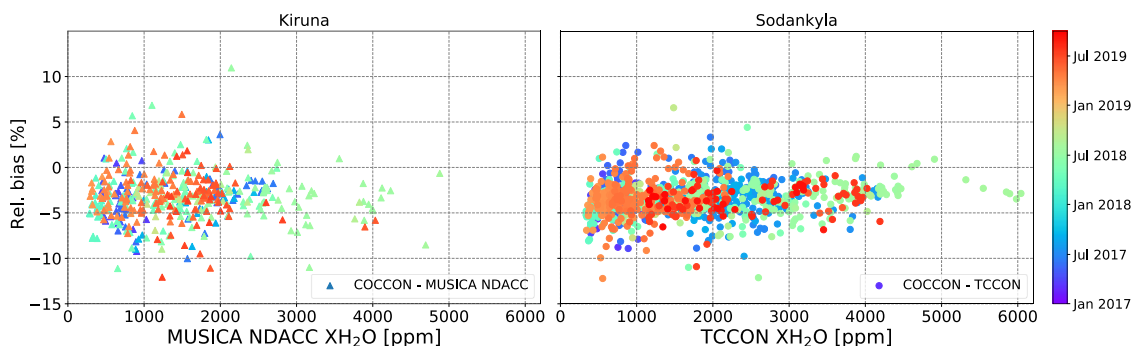
Figure 1. Time series of XH₂O derived from MUSICA IASI, TROPOMI, and ground-based FTIR instruments at (a) Kiruna and (b) Sodankylä. The corresponding relative biases are presented in the bottom panel for coincident pairs at each subfigure.

230 **4.2 Comparison between COCCON and co-located ground-based FTIR instruments**

Figure 2 gives the correlation of XH₂O measured by the COCCON instrument against coincident MUSICA NDACC retrievals for the Kiruna site (left) and against coincident TCCON retrievals for the Sodankylä site (right). In general, the two datasets at each site show quite good agreement and overall consistency, with R² value of 0.9992 for Kiruna and 0.9997 for Sodankylä. The second and seventh columns in Table 1 list the statistics for the coincident data between the COCCON and MUSICA NDACC XH₂O at the Kiruna site and between the COCCON and TCCON XH₂O at the Sodankylä site, respectively. Figure 3 shows the differences between the COCCON and the MUSICA NDACC retrievals at the Kiruna site and the differences between COCCON and TCCON retrievals at the Sodankylä site as a function of XH₂O amounts. There is no detectable dependence at both sites.



240 **Figure 2. Correlation of COCCON XH₂O and coincident MUSICA NDACC retrievals for Kiruna (left) and of COCCON and coincident TCCON retrievals for Sodankylä (right). The solid green and dashed lines denote the linear fit and one-to-one lines, respectively. Color-coded from purple to red in order of measuring time from January 2017 to October 2019.**



245 **Figure 3. XH₂O difference (COCCON – MUSICA NDACC) for Kiruna (left) and XH₂O difference (COCCON – TCCON) for Sodankylä (right) versus XH₂O amounts. Color-coded from purple to red in order of measuring time from January 2017 to October 2019.**

Figure 4 shows the XH₂O relative bias of MUSICA NDACC and TCCON compared to COCCON with respect to SZA over the whole period studied at the two stations. The absolute values of the relative bias between COCCON and MUSICA NDACC at Kiruna (left) show no obvious sensitivity to the SZA. However, the absolute value of the relative bias between COCCON and TCCON at Sodankylä becomes slightly larger with increasing SZA. This is because the TCCON and COCCON instruments have different spectral resolutions, which results in different absorption strengths and column averaging kernels (AVK) (Hedelius et al., 2016). Furthermore, the AVK also shows different sensitivity to the SZA of the measurement (Wunch et al, 2011). The AVK describes the sensitivity of the H₂O retrieval to a perturbation in the H₂O column at a given altitude. An AVK close to unity indicates maximum retrieval accuracy and an AVK larger or smaller than 1 indicate overestimation and underestimation of the true H₂O column amount, respectively.

Figure 5 depicts examples of AVKs for H₂O under different SZA on July 2nd, 2018. It reveals a sensitivity of very close to 100 % for the lowermost altitudes, where most water vapor resides. The AVK for MUSICA NDACC H₂O retrievals shows no obvious sensitivity to the SZA and altitude, and are very close to unity below 5 km. However, TCCON and COCCON AVK vary with SZA and altitude. The TCCON AVKs are smaller than 1 and increases with increasing SZA below 1.5 km, and are larger than 1 and decrease with increasing SZA upwards. This change indicates that the TCCON H₂O total column underestimates a deviation near the surface and overestimates a deviation at higher levels from the a priori profiles. The COCCON AVKs show an opposite way, with overestimations and increasing value with larger SZA below 2 km, and with underestimations and decreasing value with larger SZA upwards. The overall column sensitivities of TCCON increase with increasing altitude, while the column sensitivities of COCCON decrease with increasing altitude. TROPOMI AVKs show a decrease trend as the increasing altitude, which is similar to the COCCON AVKs. However, no obvious SZA-dependent is observed in TROPOMI AVKs. Here, an example of row AVKs at SZA = 45° and degree of freedoms (DOFS) = 5.09 is presented for IASI (Fig. 5e) and DOFS shows a positive correlation to the SZA (Fig. 5f).

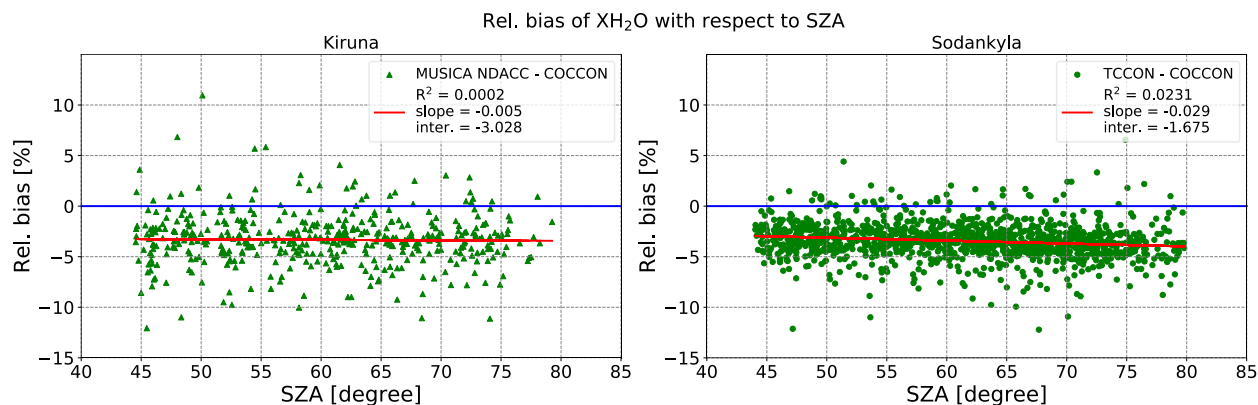


Figure 4. Dependence of the XH₂O difference (MUSICA NDACC – COCCON) at Kiruna site (left) and the difference (TCCON – COCCON) at Sodankylä site (right) on the SZA. The solid red line represents the fitting line.

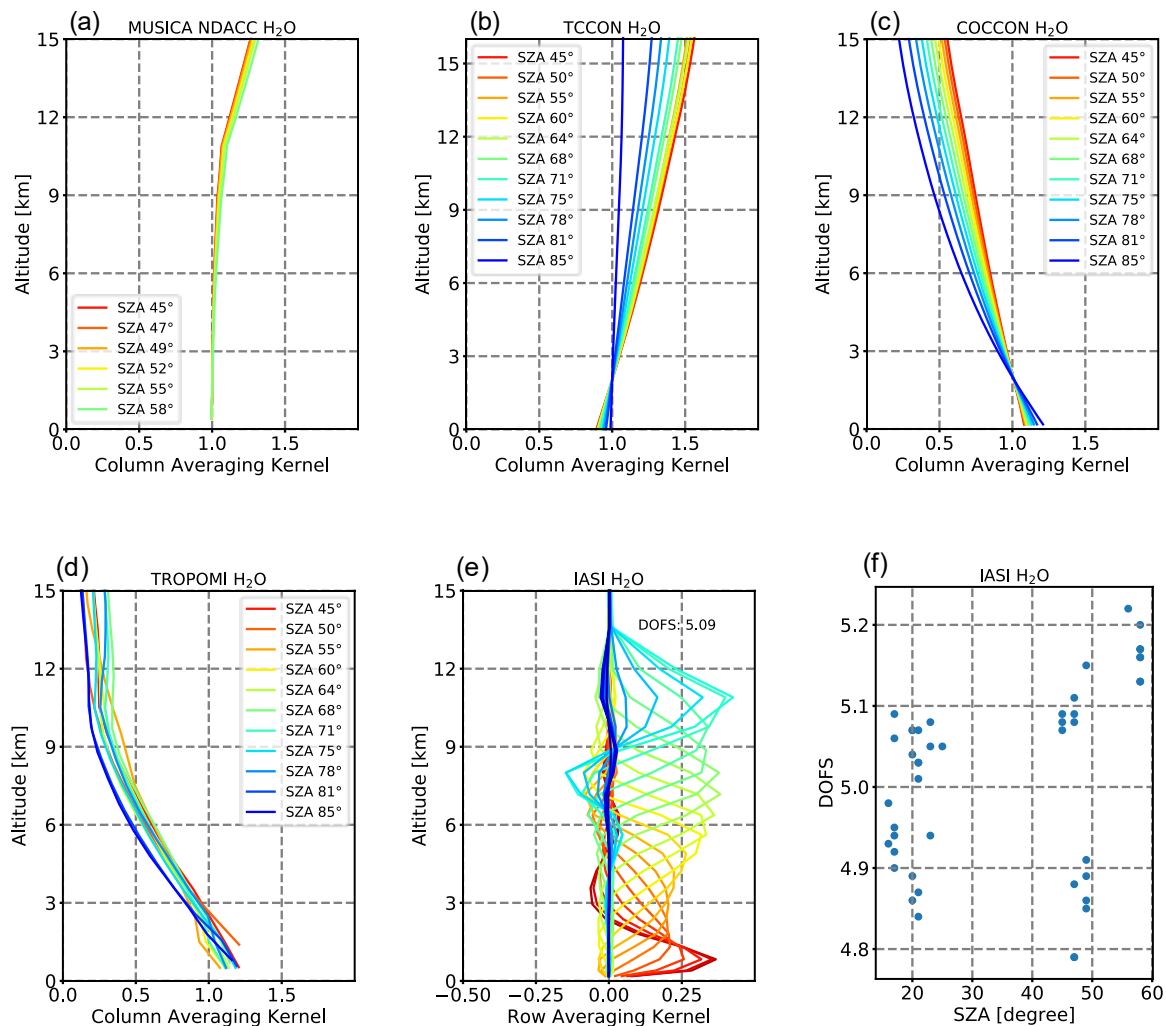


Figure 5. Examples of column averaging kernels for H₂O from (a) MUSICA NDACC, (b) TCCON, (c) COCCON and (d) TROPOMI for different SZA, (e) examples of row averaging kernel from IASI at DOFS=5.09 and (f) the correlation

275 **between SZA and DOFS for IASI on July 2nd, 2018.**

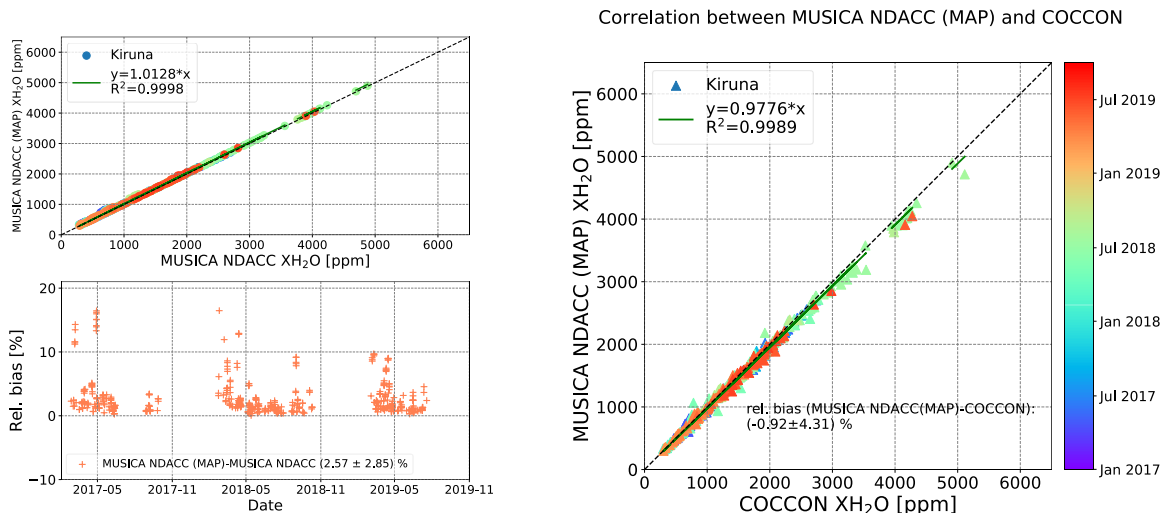
Table 1. Statistical comparison between COCCON XH₂O and other instruments at each site. The total number of coincident data (No.) is listed. The biases and relative biases are presented in terms of mean value followed by standard deviation.

	Kiruna					Sodankylä			
	MUSICA NDACC	MUSICA NDACC (MAP)	MUSICA IASI	MUSICA IASI (MAP)	TROPOMI	TCCON	MUSICA IASI	MUSICA IASI (MAP)	TROPOMI
No.	505		101		87	1355	121		59
R²	0.9992	0.9989	0.9904	0.9901	0.9950	0.9997	0.9917	0.9914	0.9961
Linear fit slope	0.9656	0.9776	1.0296	1.0404	0.9078	0.9688	1.0211	1.0375	0.9289
bias (ppm)	-49.20 ± 58.61	-24.45 ± 63.03	82.72 ± 233.35	108.54 ± 238.89	-176.55 ± 161.0	-56.32 ± 45.63	84.67 ± 251.	127.34 ± 257.81	-192.1 ± 179.49
relative bias (%)	-3.33 ± 3.37	-0.9 ± 4.31	4.46 ± 11.43	6.03 ± 11.59	-9.71 ± 7.69	-3.44 ± 1.77	3.36 ± 10.83	4.49 ± 10.86	-7.75 ± 6.45

285 When directly comparing the measurements from different remote sensing instruments, the differing observing system characteristics, particularly vertical sensitivity and a priori profiles should be considered (Rodgers and Connor, 2003). The COCCON instrument uses the same a priori H₂O VMR profiles as used in the TCCON network, derived from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) 6-hourly reanalysis data. A daily profile has been generated from the NCEP/NCAR data, interpolated to latitude, longitude and local solar noon time at
290 the site. We refer to the TCCON a priori profiles as “MAP” files, following the naming convention used for the TCCON processing. MUSICA NDACC uses a single global climatology profile as a priori, which has no seasonal variations.

To assess the impact of the a priori profiles on the retrievals, the MAP a priori profiles used in TCCON and COCCON are applied to the MUSICA NDACC retrievals and IASI retrievals. We use MUSICA NDACC (MAP) and IASI (MAP) to represent the corresponding XH₂O to distinguish the official MUSICA NDACC and MUSICA IASI data. The MUSICA IASI
295 (MAP) will be discussed in Section 5.1.

The correlation between MUSICA NDACC and MUSICA NDACC (MAP) and the time series of their relative bias are presented in Fig 6a and b. The MUSICA NDACC (MAP) XH₂O shows an excellent agreement with the MUSICA NDACC, with an R² value of 0.9998. When using the MAP profiles, the XH₂O retrievals are 2.57 % (standard deviation: 2.85 %) wetter than the MUSICA NDACC retrievals and higher relative biases are found early in the year when the atmosphere is dryer. This
300 a priori choice increases slightly the correlation between MUSICA NDACC (MAP) and COCCON retrievals with the R² value of 0.9989 and consequently the relative difference decreases to -0.92 % (standard deviation: 4.31%). This small change indicates that MUSICA NDACC XH₂O has little sensitivity to the a priori information and the bias between MUSICA NDACC and COCCON is mainly due to the choices for the calibration of the XH₂O data product by either network.



305 **Figure 6. Correlation plot of MUSICA NDACC XH₂O and MUSICA NDACC (MAP) (top left), time series of their relative bias (bottom left), and correlation plot of COCCON XH₂O and coincident MUSICA NDACC (MAP) retrievals (right) at Kiruna site. The annotations follow those in Fig. 2.**

4.3 H₂O VMR profiles from in situ radiosonde at Sodankylä site

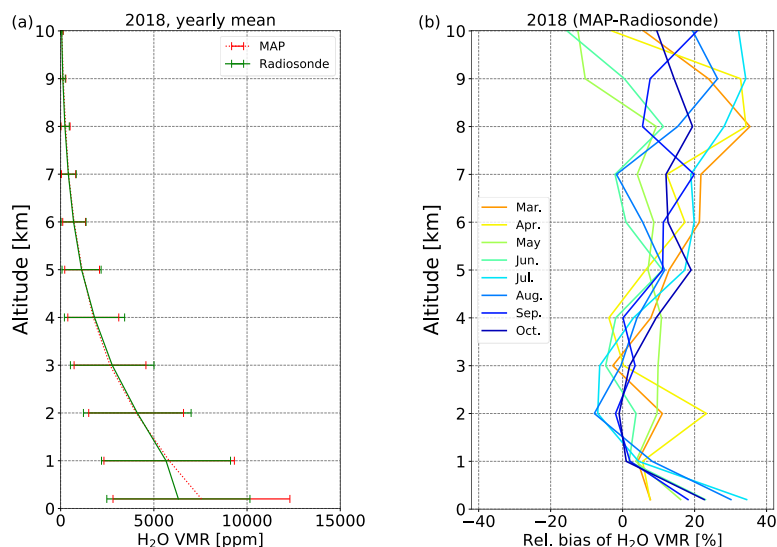
The comparison of the a priori H₂O profile used for the different instruments with in situ climatological knowledge of H₂O vertical variability yields a precision estimate for the retrievals. In this section, the MAP a priori profiles used in TCCON and COCCON are discussed using Vaisala RS41 radiosonde profiles as a reference.

The radiosondes are daily launched and the coincident MAP and radiosonde profiles cover nearly the whole year. Since most of the H₂O is located in the troposphere, we here present the profiles below 10 km. Figure 7 depicts the yearly-averaged H₂O VMR profiles derived from the MAP and Vaisala RS41 radiosonde (left panel) and the monthly-averaged relative biases between MAP and radiosonde profiles (right panel) for 2018. The ensemble of radiosonde profiles has a higher vertical resolution and is regridded to the lower vertical resolution of MAP profiles. The statistics of yearly-averaged MAP and radiosonde profiles at each level in 2018 are listed in Table 2.

The vertical H₂O VMR profiles of MAP are overestimated by 16.4 % at an altitude of 0.2 km with respect to the radiosonde profiles. The MAP profiles are generally closer to the radiosonde profiles between 1 – 4 km with a relative bias in the range of 1.1 % – 4.4 %. For the upper layers (above 4 km) MAP shows overall higher overestimations of H₂O (up to 19.4 %) than at the lower layers.

The time series of XH₂O from integrating the a priori MAP profiles and radiosonde profiles between 0.2 and 15 km is presented in Figure 8. These integrated-profile XH₂O shows similar seasonal variability as observed by COCCON and TCCON at Sodankylä. A good agreement is found for the integrated XH₂O between MAP and radiosonde profiles, with a relative bias of 3.95 % and a R^2 value of 0.9904 (Fig. 9a), indicating that the modeled MAP profiles can well represent the vertical variability of H₂O in the real atmosphere. TCCON measures 19.08 % drier XH₂O than the radiosonde with a R^2 value of 0.9952. There

is a smaller dry bias in the COCCON XH₂O with respect to radiosonde and amounts to 14.96 % ($R^2 = 0.9957$). This high bias is mainly because COCCON and TCCON measures the total column of H₂O, while the radiosonde XH₂O is integrated up to 15 km and there are remaining H₂O above this level.

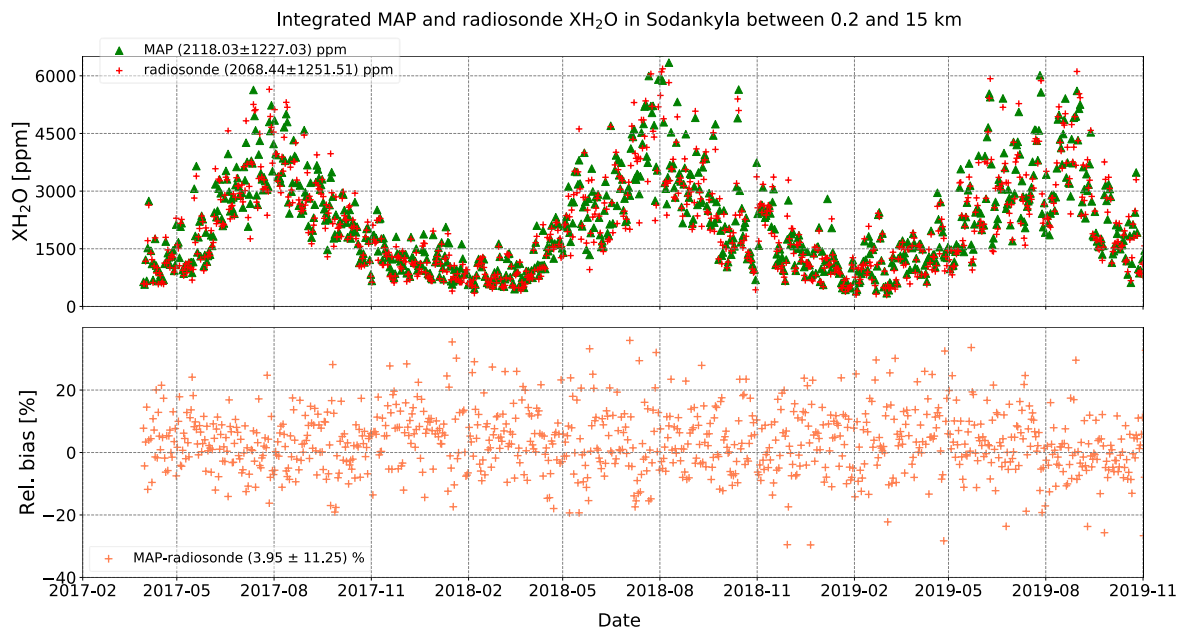


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Figure 7. (a) Yearly-averaged H₂O VMR profiles as a function of altitude retrieved from MAP (in red) and the Vaisala RS41 radiosondes (in green) around noon at Sodankylä site in 2018 (the error bar denotes the standard deviation). (b) The corresponding monthly-averaged relative bias between MAP and radiosonde profiles. Vaisala RS41 radiosonde profiles are regridded to the vertical resolution of MAP profiles.

335 **Table 2. Yearly mean and standard deviation for a priori MAP and radiosonde profiles at each level in 2018 and for their corresponding relative biases.**

Height (km)	MAP (ppm)	Radiosonde (ppm)	Rel. bias (%) MAP-Radiosonde
0.2	7554 ± 4745	6315 ± 3840	16.38 ± 18.85
1	5821 ± 3499	5652 ± 3461	3.65 ± 12.34
2	4048 ± 2543	4110 ± 2888	4.84 ± 24.55
3	2647 ± 1927	2766 ± 2242	1.06 ± 26.11
4	1751 ± 1367	1817 ± 1615	4.37 ± 32.23
5	1152 ± 933	1122 ± 1049	10.65 ± 35.54
6	722 ± 611	694 ± 671	12.33 ± 36.71
7	423 ± 383	411 ± 424	9.44 ± 40.21
8	263 ± 243	228 ± 234	19.41 ± 39.57
9	136 ± 141	116 ± 131	14.11 ± 52.02
10	63 ± 77	53 ± 63	5.43 ± 52.02



340 **Figure 8.** Time series of integrated XH₂O derived from MAP and radiosonde H₂O VMR profiles between 0.2 and 15 km. The corresponding relative biases are presented in the bottom panel.

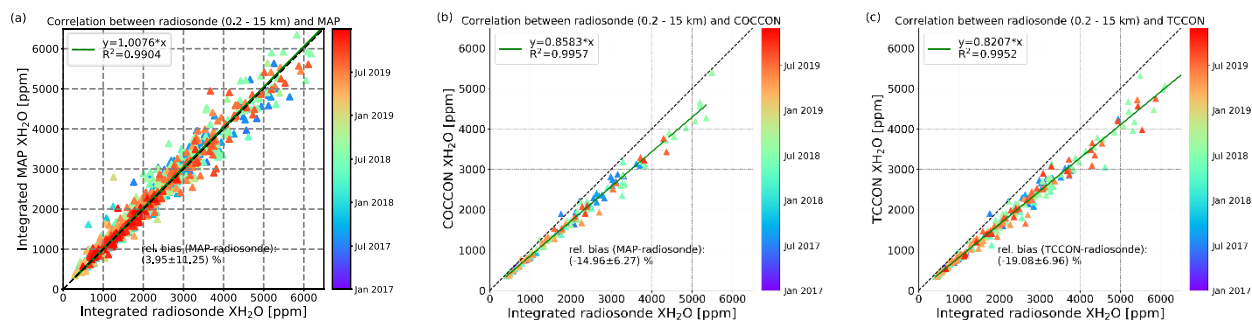


Figure 9. Correlation plots of the XH₂O derived from (a) MAP VMR profiles, (b) COCCON and (c) TCCON with respect to the XH₂O derived from coincident radiosonde profiles between 0.2 and 15 km at Sodankylä site. The annotations follow those in Fig. 2.

5. Validation of satellite XH₂O data using COCCON as the reference

345 5.1 Comparison between COCCON and MUSICA IASI

The agreements between the IASI and COCCON retrievals at two sites are presented in Fig. 10. COCCON XH₂O shows overall very good agreement with the MUSICA IASI data at both sites. For the Kiruna site COCCON measures a drier XH₂O than MUSICA IASI with a mean bias of 82.72 ppm (4.64 %) and a standard deviation of 234.56 ppm (11.43 %). COCCON measures a drier XH₂O at Sodankylä with a mean bias of 84.67 ppm (3.36 %) and a standard deviation of 252.26 ppm (10.83 %)

350 % with respect to MUSICA IASI. The coincident data between COCCON and MUSICA IASI show higher variations

(standard deviation) than the coincident data between COCCON and ground-based MUSICA NDACC and TCCON. This is mainly because the IASI data is collected from a wide area around the ground-based FTIR stations and the varying altitudes also introduce additional biases. Partly cloudy conditions introduce biases to the IASI measurements, even if the cloud filter is applied. The fourth and eighth columns in Table 1 list the statistics between the coincident MUSICA IASI and COCCON XH₂O data at two sites.

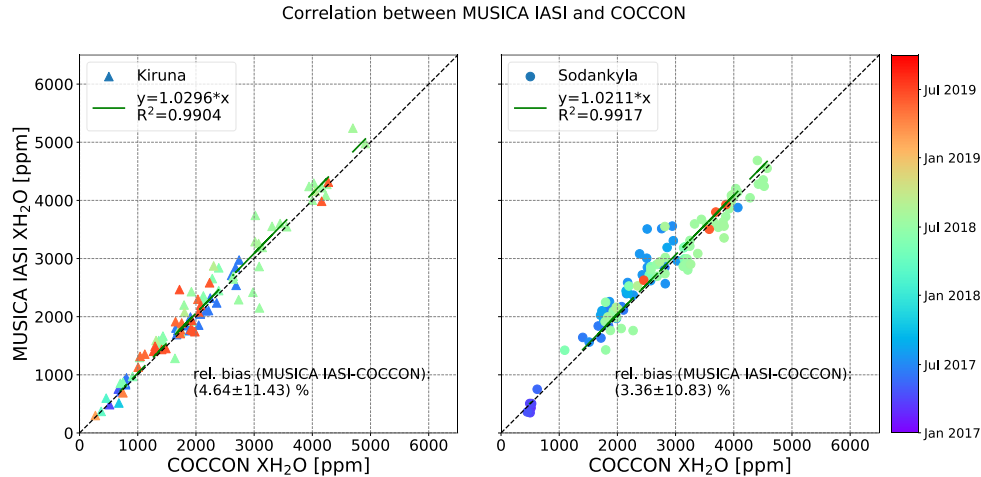
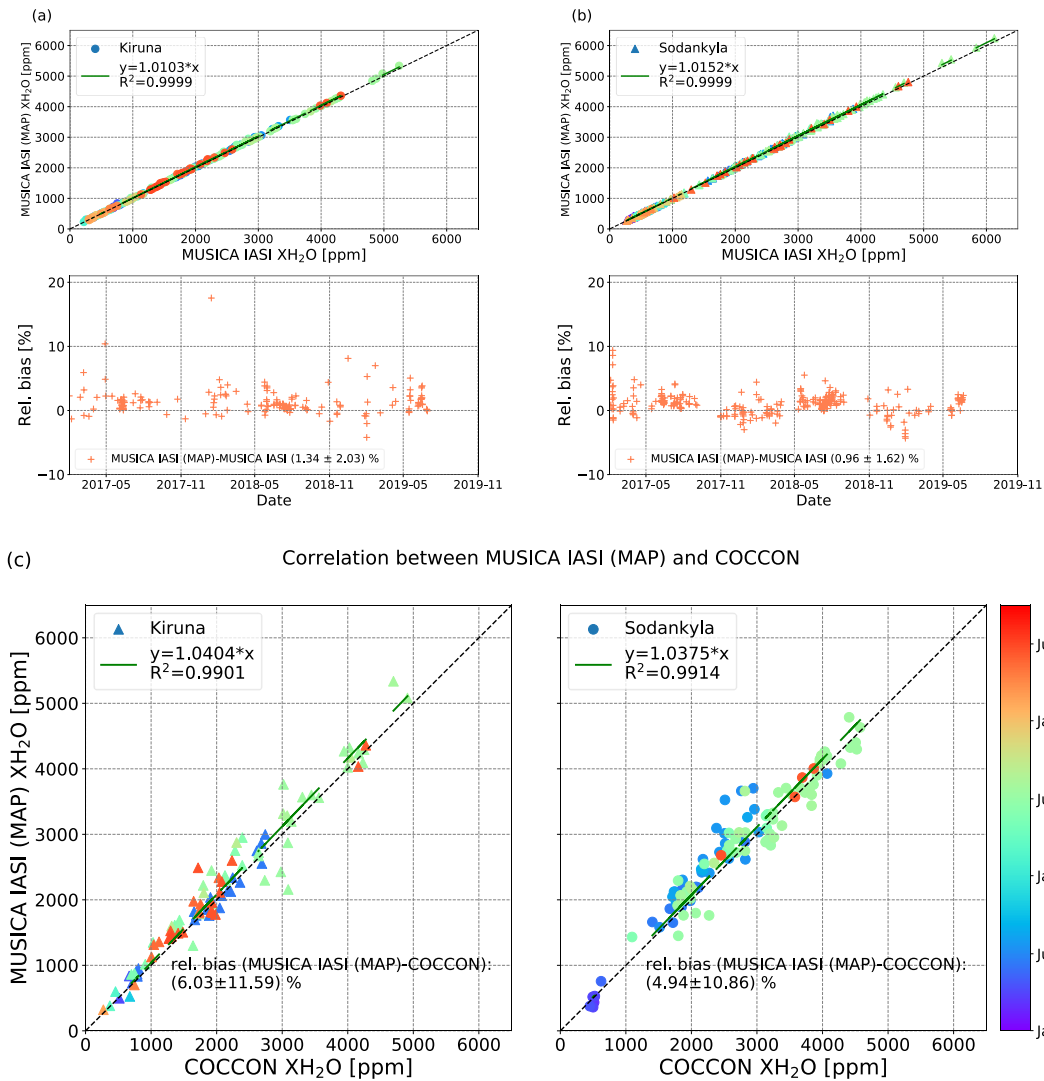


Figure 10. Scatter plot of the COCCON XH₂O compared to coincident MUSICA IASI retrievals at Kiruna site (left) and Sodankylä site (right). The annotations follow those in Fig. 2.

Similar to the MUSICA NDACC (MAP) XH₂O, the application of MAP as a priori profiles does not impact the MUSICA IASI (MAP) too much. Figure 11a and b illustrate the correlations between the MUSICA IASI (MAP) and MUSICA IASI and the time series of their relative biases at Kiruna and Sodankylä. The two datasets at each site show an excellent agreement, with the same R² value of 0.9999. The MUSICA IASI (MAP) XH₂O is larger by 1.34 % and 0.96 % compared to MUSICA IASI retrievals at Kiruna and Sodankylä, respectively. These wetter retrievals result in increases in the relative biases between MUSICA IASI (MAP) and COCCON to 6.03 % at Kiruna and to 4.94 % at Sodankylä, respectively. In general, MUSICA IASI (MAP) also agrees very well with COCCON (see Fig. 11c) similar to the correlation between MUSICA IASI and COCCON, which reveals that the a priori profiles have small impact on the MUSICA IASI XH₂O and the bias between MUSICA IASI and COCCON is mainly due to the choices for the calibration of XH₂O data product by either dataset.



370 **Figure 11.** Correlation plots of MUSICA IASI XH₂O and MUSICA IASI (MAP) and time series of their relative difference at Kiruna site (a) and Sodankylä site (b), and correlation plot of COCCON XH₂O and coincident MUSICA IASI (MAP) retrievals at two sites (c). The annotations follow those in Fig. 2.

5.2 Comparison between COCCON and TROPOMI

The correlation plots between TROPOMI and COCCON XH₂O data at Kiruna and Sodankylä sites are presented in Fig. 12 and the sixth and tenth columns in Table 1 list the statistics for each site. The TROPOMI XH₂O shows generally good agreement with COCCON data and the correlations at both sites are similar. The slope demonstrates an underestimation of the TROPOMI retrievals vs. COCCON retrievals, with a factor of 0.9078 in Kiruna and 0.9289 in Sodankylä. The total bias is –176.55 ppm (–9.71 %) with a standard deviation of 161.0 ppm (7.69 %) and the correlation coefficient is 0.9950 at Kiruna.

375

The correlation at Sodankylä is slightly better, with a correlation coefficient of 0.9961, a mean bias of -192.1 ppm (-7.75%),
 380 and a standard deviation of 179.49 ppm (6.45%).

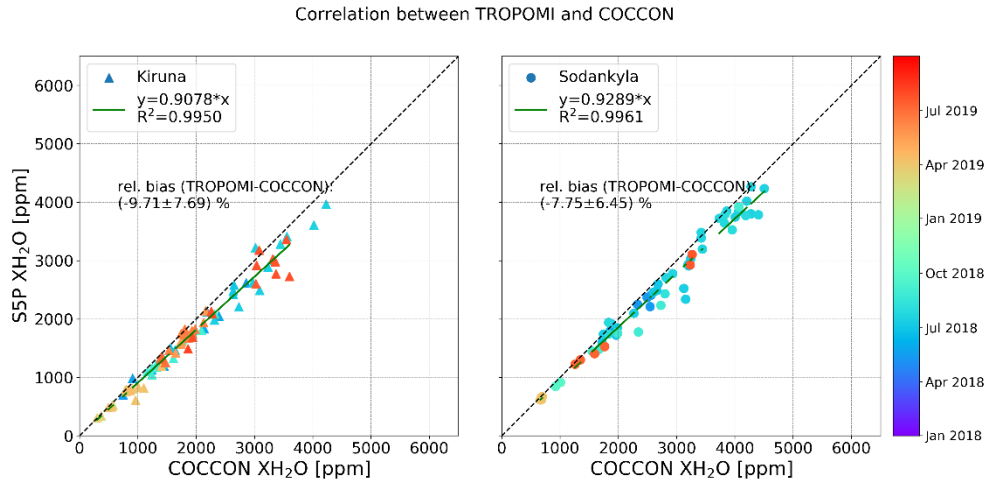


Figure 12. Correlation plots of TROPOMI and COCCON XH₂O at Kiruna site (left) and Sodankylä site (right). The annotations follow those in Fig. 2. Noted that the color bar is from January 2018 to October 2019.

6. Summary and conclusions

385 In this paper, we compare the column-averaged dry-air mole fractions of water vapor (XH₂O) retrievals from COCCON and MUSICA NDACC at Kiruna and from COCCON and TCCON at Sodankylä during the period of March 2017 – September 2019. Additionally, we evaluate the vertical water vapor VMR profiles (MAP) as a priori used in COCCON and TCCON retrievals with in situ profiles retrieved from the radiosonde Vaisala RS41.

We found a very good agreement between the COCCON and the MUSICA NDACC data at Kiruna and between the
 390 COCCON and the TCCON data at Sodankylä. The COCCON retrievals have a tendency toward a wet bias of (-49.20 ± 58.61) ppm ($(-3.33 \pm 3.37)\%$) at Kiruna and (-56.32 ± 45.63) ppm ($(-3.44 \pm 1.77)\%$) at Sodankylä. The relative bias between COCCON and MUSICA shows no obvious sensitivity to the SZA, whereas, the absolute value of the relative bias between COCCON and TCCON becomes slightly larger with increasing SZA over 70° . This is because the TCCON and COCCON instruments have different spectral resolutions, which results in different absorption strengths and also averaging kernels
 395 (Hedelius et al., 2016).

The a priori profiles play an important role in the retrievals. The in situ measured vertical H₂O VMR profiles performed at Sodankylä provide the possibility to evaluate the a priori profiles (MAP) used in both COCCON and TCCON datasets. Since the shapes of profiles are similar over the years, we investigate the profiles in 2018 as an example. The difference between the MAP and radiosonde profiles varies with season and height, and higher differences are found near the surface in summer. The
 400 XH₂O amounts integrated from MAP and radiosonde profiles between 0.2 km to 15 km show a very good agreement ($R^2 = 0.9904$), indicating that MAP profiles are reasonably modeled and represent the vertical variability well. Compared to

radiosonde, both COCCON and TCCON measure drier XH₂O with mean biases of 14.96 % and 19.08 %, respectively. These high biases are mainly because COCCON and TCCON measures the total column of H₂O, while the radiosonde XH₂O is only integrated up to 15 km and there are remaining H₂O above this level.

405 Secondly, comparisons between the COCCON and MUSICA IASI datasets at Kiruna and Sodankylä are also carried out and they show overall good agreement. COCCON measures a drier XH₂O against MUSICA IASI with a mean bias of 82.72 ppm (4.46 %) at Kiruna and with a mean bias of 84.67 ppm (3.36 %) at Sodankylä. However, COCCON measures a wetter XH₂O against TROPOMI data with a mean bias of -176.55 ppm (-9.71 %) at Kiruna and with a mean bias of -192.1 ppm (-7.75 %) at Sodankylä. The higher biases between COCCON and satellites is mainly because the satellite data are collected
410 from a wide area around the ground-based FTIR stations and the varying altitudes also add a bias.

To assess the effect of the a priori profile, we also use the MAP profiles as a priori profiles for retrieving the MUSICA NDACC and MUSICA IASI XH₂O. The MUSICA NDACC (MAP) and MUSICA IASI (MAP) agree very well with their original dataset ($R^2 \geq 0.9998$), with no significant seasonal variations. When applying the MAP a priori profiles, we observe an overall increase in MUSICA NDACC (MAP) by 2.57 % in Kiruna, and an increase in MUSICA IASI (MAP) by 1.34 % in
415 Kiruna and by 0.96 % in Sodankylä, respectively. Therefore, MUSICA NDACC and MUSICA IASI XH₂O show small sensitivity to the a priori profiles. The small biases between the MUSICA NDACC and COCCON and between MUSICA IASI and COCCON are mainly from the calibration choices of the XH₂O data product.

During this field campaign the low-cost and portable COCCON instrument shows its advantage of robustness, stability and reliability, which provides the potential to complement the TCCON network and for satellite validation. This is the first
420 published study where COCCON XH₂O is compared with MUSICA NDACC and TCCON retrievals, and for MUSICA IASI and TROPOMI validation. Therefore, COCCON instrumentation may also serve as validation tool for space-borne XH₂O measurements, additionally to XCO₂ and XCH₄.

Author contributions. Frank Hase, Matthias Schneider and Qiansi Tu developed the research question. Qiansi Tu wrote the manuscript and performed the data analysis with support from Frank Hase, Thomas Blumenstock, Matthias Schneider, Andreas Schneider, Rigel Kivi, Pauli Heikkinen and Michael Sommer. Qiansi Tu, Thomas Blumenstock, Pauli Heikkinen, Rigel Kivi and Uwe Raffalski took an active part in the field campaign by operating the COCCON spectrometers and collecting data. Rigel Kivi and Pauli Heikkinen also operate the TCCON station at Sodankylä site and provided data. Andreas Schneider and Tobias Borsdorff provided the TROPOMI satellite data and gave technical support for the analysis. Matthias Schneider, Benjamin Ertl, Christopher Diekmann, and Farahnaz Khosrawi provided the MUSICA data. All authors discussed the results and contributed to the final manuscript.

Data availability. The TCCON GGG2014 data are publicly available from the TCCON Data Archive (<https://doi.org/10.14291/tccon.ggg2014.sodankyla01.r0/1149280>, Kivi et al., 2014). MUSICA NDACC data are available from <ftp://ftp.cpc.ncep.noaa.gov/ndacc/MUSICA/>. Global MUSICA IASI data will very soon be publicly available, since then they can be requested by email from Matthias Schneider. The S5P dataset is available at ftp://ftp.sron.nl/open-access-data-2/TROPOMI/tropomi/hdo/9_1/.

Competing interests. The authors declare that they have no conflict of interest.

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Appendix

Table A 1. Parameters of different instruments used in this study.

	COCCON	TCCON	MUSICA NDACC	MUSICA IASI	TROPOMI
Spectral window (cm⁻¹)	8353.4 – 8463.1	6076.90 – 6469.60 (Wunch et al., 2010)	2658 – 3053	1190 – 1400	4200.8 – 4248.1 (Scheepmaker et al., 2016)
Spectroscopic modelling	HITRAN 2009	HITRAN 2009	HITRAN 2012 with modifications to consider speed-dependent Voigt line shapes (Barthlott et al., 2017)	HITRAN 2016, Voigt line shapes Water vapor continuum model: MT_CKD v2.5.2 (Delamere et al., 2010; Payne et al., 2011; Mlawer et al., 2012)	HITRAN 2016
A priori H₂O	NCEP/NCAR ¹	NCEP/NCAR	Globally mean WACCM ² profile. No latitudinal and seasonal dependence	Latitudinal-and-seasonal dependent WACCM climatology	ECMWF ³
Calibration factor	0.830	1.0 (Wunch et al., 2011)	0.88	None	None
Number of degrees of freedom			2.8	4-5	

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