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Integrated water vapor above Ny Ålesund, Spitsbergen: a multisensor intercomparison

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Abstract

Water vapor is an important constituent of the atmosphere. Because of its abundance it plays an important role for the radiation budget of the atmosphere and has major influence on weather and climate.

In this work the integrated water vapor (IWV) measurements derived from the measurements of two satellite sensors, SCIAMACHY and AMSU-B, and two ground-based sensors, a Fourier-transform spectrometer (FTIR) and an O_3 microwave ozone sensor (RAM), are compared to radio-sonde measurements in Ny Ålesund, 79° N. All four remote sensors exploit different principles and work in different wavelength regions. Combined they deliver a comprehensive picture of the IWV above Ny Ålesund.

The ground-based FTIR reproduces the radio-sonde measurements very well and also shows a high correlation and very little scatter of about 10%. The other remote sensing instruments show a good correlation with the coincident radio-sonde measurements but show high scatter of about 20% (standard deviation). The ground-based RAM performs similar to the satellite instruments, which is somewhat surprising, because measuring IWV is only a by-product for this sensor.

The RAM sensor records a measurement every hour and is therefore suited to observe the diurnal variation. As measured by the RAM and FTIR the variance within 4 h is often in excess of 50% (minimum – maximum of the measured IWV). This large variance in the integrated water vapor renders the comparison of different sensors a difficult task. The derived variance of the instruments when compared to radio-sonde measurements can be explained by the high natural variability of IWV.

1 Introduction

Water vapor is the most abundant trace gas in the troposphere. Due to its radiative properties it contributes a large part to the atmosphere's radiation budget. It influences the climate due to cloud and ice formation and is responsible for most of the weather.

Hence, the integrated water vapor (IWV) is an important factor for short term weather prediction.

Because of the large gradient of the volume mixing ratio (VMR) from the ground to the tropopause (approx. 10 000 ppm at the ground to approx. 4 ppm at the tropopause) and its radiative properties due to its large amount in the troposphere, the measurement of water vapor is a demanding task.

Several techniques are employed to retrieve IWV information as well as profile information from atmospheric measurements. These include in-situ techniques like radiosondes and remote sensing from ground, aircraft and satellites. In Sect. 3.2 four passive remote sensors (for a detailed description see Sect. 2), which operate at different wavelengths and exploit different radiative properties in order to derive IWV are compared to radio-sonde measurements of IWV. In Sect. 3.3 measurements from the satellite based instruments AMSU-B and SCIAMACHY are compared to measurements taken by a ground-based Fourier-transform spectrometer (FTIR) in order to exclude cloudy conditions.

In Sect. 4 a study of the variance of IWV above Ny Ålesund is conducted. The high variance found puts limits on the expected quality of the intercomparison in terms of the scatter of the remote sensing instruments around the true value, which is caused by temporal and spatial deviation.

All measurements have been performed in the high Arctic, near the town of Ny Ålesund, 79° N.

2 Instrumentation

2.1 The AWIPEV research base Ny Ålesund

Ny Ålesund is a village on the Spitsbergen archipelago at 78.9° N, 11.9° E. The research base AWIPEV is operated jointly by the French Polar institute IPEV[1] and

[1]**I**nstitut **P**aul **E**mile **V**ictor, http://www.institut-polaire.fr

the German polar institute AWI[2]. The AWIPEV research base has been recognized as a primary NDACC[3] research station. Among several other NDACC instruments (LIDAR[4], DOAS[5], radio-sondes) a Bruker 125 HR FTIR[6]-spectrometer (1992–1996: Bruker 120M) and the microwave radiometer RAM[7] are operated on the AWIPEV station. Regular FTIR measurements in solar and lunar absorption (Notholt et al., 1995) have been conducted since 1993. The RAM started operational measurements in 1996 (Klein et al., 2002).

2.1.1 Radio-sondes at Ny Ålesund

Apart from launches during campaigns, radio-sondes are launched every day at 11 a.m. UTC from the AWIPEV research base. Until August 2002 the type Vaisala RS-80 was used and has been replaced by the type Vaisala RS-90. Since September 2003 the type Vaisala RS-92 is used for the regular soundings.

The radio-sonde launches are provided for and performed by the AWI Germany.

2.1.2 FTIR spectrometer at Ny Ålesund

The FTIR spectrometer on Ny Ålesund is operated in solar or lunar absorption mode whenever weather conditions permit. Due to the measurement principle a clear sight of the illuminating object (Sun or Moon) is necessary during the measurement which takes up to 30 min. Usually FTIR measurements are performed when there are very stable weather conditions and a largely cloud-free sky.

[2]**A**lfred-**W**egener-**I**nsitut, http://www.awi.de

[3]**N**etwork for **D**etection of **A**tmospheric **C**omposition **C**hange, http://www.ndacc.org

[4]**Li**ght **D**etection and **R**anging, an active remote sensing technology

[5]**D**ifferential **O**ptical **A**bsorption **S**pectroscopy

[6]**F**ourier **T**ransform **I**nfra **R**ed, http://www.iup.uni-bremen.de/ftir

[7]**R**adiometer for **A**tmospheric **M**easurements, http://www.iup.uni-bremen.de/ram

In the work presented, the wavenumber region around 3300 cm^{-1} has been used to derive IWV above Ny Ålesund. For the wavenumber region at 3300 cm^{-1} an Indium-Gallium-Arsenide (InSB) detector cooled with liquid nitrogen and a CaF_2 beam splitter is used. A Signal-to-Noise-Ratio (SNR) of better than 1400 can regularly be obtained for measurement times of about 10 min in solar absorption spectroscopy. An SNR of about 100 for measurement times of about 30 min is obtained during winter in lunar absorption mode. The HITRAN database (Rothman et al., 2003, version2k + updates from 2006) has been used to analyze the spectra.

The spectra are analyzed using the software SFIT2 (Hase et al., 2004), version 3.93, extended to work with logarithmic state vectors. This has been proven advantageous in the case of water vapor (Schneider et al., 2006).

The spectrometer is regularly checked and adjusted using the program LINEFIT (Hase et al., 1999).

2.1.3 Microwave spectrometer RAM on Ny Ålesund

Since 1994 the microwave radiometer RAM measuring the 142 GHz emission of O_3 is operated at the AWIPEV base in Ny Ålesund (e.g. Klein et al., 2002). While the main purpose of this instrument is monitoring stratospheric O_3, IWV can be derived as a by-product.

The spectra are evaluated on an operational basis using the software package QPACK/ARTS (Eriksson et al., 2005; Bühler et al., 2005, ARTS version 1.0). Beside the O_3 VMR profile, the tropospheric opacity τ is derived during the analysis. Under the assumption that (I) the atmosphere is mainly composed of Oxygen and water vapor, (II) the absorption cross sections of water vapor α_{H_2O} are constant and (III) no scattering occurs, τ can be used to calculate the IWV, C_{H_2O}, via

$$C_{H_2O} = \frac{\tau - K}{\alpha_{H_2O}}. \quad (1)$$

The contribution of Oxygen to the opacity, K, and the absorption cross sections, α_{H_2O},

were determined using the radiative transfer model MWMOD (developed at the Universität Kiel; Karstens et al., 1994). For overcast conditions an empirically determined correction following Wohltmann (2002) is applied: The IWV for 100% relative humidity at all altitude levels is denoted by C_{max}. If the relative humidity is larger than 100% the IWV is corrected by:

$$C_{WET} = C_{H_2O} + 0.0073\Delta C^2 - 1.07\Delta C - 2.7384 \quad (2)$$

where $\Delta C = C_{H_2O} - C_{max}$.

2.2 SCIAMACHY onboard ENVISAT

SCIAMACHY (Scanning Imaging Absorption Spectrometer for Atmospheric Chartography) is a spectrometer designed to measure sunlight transmitted, reflected, and scattered by the Earth's atmosphere or surface in the ultraviolet, visible, and near-infrared wavelength region (214 to 2386 nm) at moderate spectral resolution (0.2–1.5 nm). SCIAMACHY is part of the payload of ESA's Environmental Satellite ENVISAT, launched in March 2002. Since then, SCIAMACHY measures the earth-shine radiance in limb- and nadir- viewing geometries and solar or lunar light transmitted through the atmosphere observed in occultation. Operational data products are provided regularly since August 2002.

The spatial resolution in nadir mode is a function of wavelength and orbital position, limited on the one hand by the intensity of the incoming radiation and on the other hand by the available data rate. The typical SCIAMACHY ground pixel size in nadir is about 30 km×60 km. After May 2004 the on-board instrumental setup has been changed to measure even smaller ground pixel sizes in certain situations.

IWV is derived using the Air Mass Corrected Differential Optical Absorption Spectroscopy (AMC-DOAS) approach (Noël et al., 2004) using water vapor and molecular oxygen absorption between 688 and 700 nm. The AMC-DOAS method has also been applied successfully to measurements of GOME (Global

Ozone Monitoring Experiment, Burrows et al., 1999), on ERS-2 and GOME-2 on Metop (Noël et al., 1999, 2008).

2.3 AMSU-B onboard NOAA-15, NOAA-16 and NOAA-17

The Advanced Microwave Sounding Unit B (AMSU-B) (Saunders et al., 1995) is part of the Advanced TIROS Operational Vertical Sounder (ATOVS), a collection of sensors flown on the polar orbiting satellites of NOAA[8] since the satellite NOAA-15 (operational since December 1998). AMSU-B is a cross-track scanning radiometer with five channels: two window channels (no strong absorption lines) at 89 and 150 GHz, and three channels close to the strong water vapour absorption line at 183.3 GHz. The imaged strip (swath) is about 2000 km wide, and the resolution on the ground is between about 15 and 50 km, increasing from the center to the edge of the swath. The outward edge of the swath corresponds to a maximum scanning angle of 48.95° off-nadir. Since there are about 14 sun-synchronous, near-polar satellite passes a day, the whole globe is covered once daily, with a lot of overlap in the polar regions. Starting with satellite NOAA-18 (launched 2005, operational since August 2005), AMSU-B has been replaced by the microwave humidity sounder (MHS) which has similar channels, but better performance.

In polar regions, where standard humidity sounding (for which AMSU-B has been designed) does not work, the water vapour column can be retrieved with the method described by Melsheimer and Heygster (2008). It derives the water vapour column from ratios of channel differences, and is independent of daylight and water clouds. In dry conditions, i.e., IWV values up to about 25×10^{21} molec/cm^2, the method works over any surface (land, sea, sea ice); in more humid conditions (up to 70×10^{21} molec/cm^2),

[8] **N**ational **O**ceanic and **A**tmospheric **A**dministration of the USA

it works only over sea ice.[9]

2.4 A note on errors

The error bars given for all remote sensing instruments are based on the noise of the measurements. A detailed error analysis has not been attempted in this work, because of the sparse input on uncertainties especially for atmospheric data. Instead, the deviation of the measurements from a common denominator will be used to draw some information about systematic and statistical errors (compare Sect. 3.2).

3 Intercomparison of measurements

An overview over all measurements taken above Ny Ålesund is given by Fig. 1. All sensors capture the seasonal cycle and also reproduce the radio-sonde measurements. It can be seen that for the highest values (IWV of more than 50×10^{21} molec/cm^2), only the radio-sondes and the SCIAMACHY instrument produce sensible results. While the FTIR would be able to measure such high values, it is restricted to clear sky when such high values of IWV are not observed at Ny Ålesund.

For the comparison, the IWV measurements of one instrument have been chosen to be the standard. The other instruments are compared against this standard. The intercomparison has been split into two parts which are distinguished by the standard which is applied. In the first part, IWV values derived from the remote sounding instruments are compared with values obtained from radio-sonde launches. The second

[9] Factors to other common units for IWV:

1×10^{21} molec/cm^2 $\hat{=}$ 0.3 kg/m^2

1 kg/m^2 $\hat{=}$ 0.1 g/cm^2 $\hat{=}$ 1 mm (liquid water)

part applies the FTIR IWV measurements as the standard. The reason for choosing two different standards is the fact that the FTIR measurements are conducted during clear sky, which increases the chance that the IWV stays stable for a few hours.

The position of the measurement of the radio-sonde is difficult to determine, because, depending on wind conditions, the horizontal movement may easily amount to several 100 km during the ascent.

We assumed, however, that the measurement takes place at Ny Ålesund. This can be justified by keeping in mind that the major part of the IWV is in the lowest few kilometers which are traversed by the radio-sonde in a few minutes with only a few km displacement.

3.1 Matching criteria

The radio-sonde, FTIR, and RAM measurements are conducted at the same place, just meters apart from each other. Because of the working principle, however, only the RAM is measuring the same point every time. The flight-path of the radio-sonde is determined by wind, and the viewing-path of the FTIR is determined by the sun and hence the time of day.

Assuming a wind speed of 10 m/s the radio-sonde travels about 36 km during 1 h. Setting the time criterion of a match to ±2 h the air-masses travel about the radius of the satellite footprints.

The same time criterion has also been chosen for the RAM and the FTIR measurement because the points of measurements at 5 km altitude may be 50 km apart under worst circumstances.

An exception is the lunar absorption measurement. The measurements are often taken during night, well apart from the radio-sonde launches. The time criterion has therefore been extended to 12 h before and after the radio-sonde launch in order to find coincidences. The FTIR lunar measurements are therefore included for informational purposes only.

For the satellite measurements an additional, spatial, condition is enforced. For

SCIAMACHY measurements only those soundings were used which cover the location of Ny Ålesund. For AMSU-B, all measurements within a circle of 50 km radius around Ny Ålesund have been integrated.

A tracing of air-masses has not been conducted because Spitsbergen has mountains rising to 1000 m altitude and more which are expected to alter the general direction and speed of air masses traversing Spitsbergen.

The distribution of the matches for the different instruments are plotted in Fig. 2. The matches for all instruments are well distributed during the time of their respective measurement set.

Summary of the matching criteria

GROUND-BASED SOLAR FTIR. An FTIR measurement is said to be coincident if it has been recorded within ±2 h of the radio-sonde launch.

GROUND-BASED LUNAR FTIR. For the lunar FTIR measurement a wide time criterion of ±12 h has to be chosen in order to find any coincidences at all. The wide criterion is reflected in the weak performance compared to the radio-sonde measurement.

GROUND-BASED MICROWAVE (RAM). A RAM measurement is said to be coincident if it has been recorded within ±2 h of the radio-sonde launch.

SCIAMACHY. A SCIAMACHY measurement is said to be coincident if the location of Ny Ålesund (78.9° N, 11.9° E) is within the SCIAMACHY ground pixel and the measurement time is within ±2 h of the radio-sonde launch.

AMSU-B. An AMSU-B measurement is said to be coincident if at least 5 ground pixels are within a radius of 50 km from the location of Ny Ålesund and the measurement time is within ±2 h of the radio-sonde launch.

3.2 Comparison of radio-sondes and remote sensing instruments

3.2.1 Methodology

Data derived from remote sensing measurements have been compared to IWV derived from radio-sonde humidity measurements.

Especially for low temperatures the radio-sonde values of the subtype Vaisala RS-80 (in use up to August 2002 in Ny Ålesund) are systematically low (Treffeisen et al., 2007). It is assumed, however, that the very low temperatures frequently occur in altitudes above 5 km which do not contribute much to the IWV.

In Fig. 3, left panel, the IWV derived from the different remote sensing instruments, c_R, versus the IWV derived from radio-sonde measurements, c_S, is plotted. A line, with gradient m and offset b, has been fitted via linear regression for coincident IWV measurements with index i:

$$(m, b) = \arg\min \left((c_{Ri} - (mc_{Si} + b))^2 \right) \tag{3}$$

The errors for the remote sensing instruments have been omitted in the plot, but have been taken into account for the calculation of the error of m and b. The factors m and b are summarized in Table 1. In order to calculate the scatter, the standard deviation of the distance of the values c_R from the line (Eq. 3) in the ranges

$$\left[i \times 5 \times 10^{21}\,\frac{\text{molec}}{\text{cm}^2} \ldots (i+1) \times 5 \times 10^{21}\,\frac{\text{molec}}{\text{cm}^2} \right] \; i = 0 \ldots 11 \tag{4}$$

has been calculated and plotted in Fig. 3, right panel.

3.2.2 Results

All remote sensing instruments capture the radio-sonde measurements well. All remote sensing instruments show a dry bias with respect to the radio-sonde data.

The FTIR measurements show very low scatter in solar absorption mode. In lunar absorption geometry the scatter around the fitted line is very high for the FTIR instrument. This is explained by the rather low SNR compared to the solar absorption measurement and by the loose temporal coincidence criterion (12 h before and after the time of the radio-sonde launch). The FTIR measurements are usually performed during clear sky. It is therefore likely that the dry bias for the FTIR is caused by a spectroscopic error. This is however part of a further investigation because a simple ad hoc correction of the spectroscopic parameters did not lead to a better result.

The IWV measured by the SCIAMACHY instrument shows a deviation of 20% from the fitted line. This may be explained by the spatial variation and by interference of clouds. This effect will be investigated further in Sect. 3.3.

The microwave instrument and the AMSU-B instrument operate at very low frequencies in the mm-wavelength range. Scattering by water clouds can largely be neglected. Ice clouds, however, are expected to lead to higher standard deviation in case of the AMSU-B instrument as well as a dry bias (Miao, 1998). The AMSU-B measurements are suited best to cold and dry conditions (Melsheimer and Heygster, 2008). They show a deviation of the IWV from the fitted line of about 20% to 30% and become unreliable for more than 30×10^{21} molec/cm^2 measured by radio-sonde. The exact type of deviation for high IWV, a non-linearity or just high scatter, cannot be determined due to the sparseness of measurements.

The ground-based microwave-instrument RAM exhibits a rather large scatter around the mean (fitted line) value. This is expected because the instrument is not designed for measuring IWV. It can still be considered a valuable complement to the ground-based FTIR instrument, because of its ability to measure during the polar night and/or cloudy conditions and the high number of measurements due to its automatic operation.

3.3 Comparison of IWV derived from FTS and satellite measurements

3.3.1 Methodology

The IWV values derived from the FTIR measurements, c_F, are compared to IWV measurements, c_S, from the satellite instruments (see Fig. 4, left panel): SCIAMACHY on board Envisat and AMSU-B on board NOAA-17. For the second step, matches are included which are both within ±2 h of the FTIR measurement and within ±2 h of the radio-sonde launch. A FTIR measurement and the radio-sonde launch may therefore be 4 h apart. This is valid because the FTIR measurements are taken during stable meteorological conditions. Again, a linear regression has been performed, this time with the FTIR IWV, c_F, as the standard. The index i denotes the number of the coincident pair: (m,b)=arg min$((c_{Si}-(mc_{Fi}+b))^2)$. The parameters m and b are documented in Table 2. The regression for the satellite measurements coinciding with both, the FTIR and the radio-sonde measurement is plotted in Fig. 4, right panel. The results are summarized in Table 3.

3.3.2 Results

The SCIAMACHY dataset overestimates the IWV with respect to the FTIR measurements. At first sight this is contradictory to the results obtained earlier in Sect. 3.2.2 and Table 1. Comparing the results for FTIR versus radio-sonde and SCIAMACHY versus radiosonde in Fig. 3, left panel, as well as in Table 1 leads to the expectation that the SCIAMACHY measurements underestimate the IWV with respect to the FTIR measurements as well. However, Fig. 4, left panel, and Table 2 show that this is clearly not the case. Comparing the IWV derived from SCIAMACHY measurements which match the FTIR measurements and the radio-sonde measurements compare very well to the radio-sonde measurements. The comparison, Fig. 4, right panel, and Table 3 hints at the solution: The FTIR measurements are usually performed if the sky is cloud-free. This leads to a special subset of SCIAMACHY measurements to be chosen. Only

measurements which are taken at very low cloud coverage are picked and compared to the FTIR measurements. Hence, the subset which is chosen for the comparison influences the results of the comparison to a large degree.

The AMSU-B measurements are consistent with the results obtained in Sect. 3.2.2 and summarized in Table 1. The FTIR and AMSU-B measurement underestimate the IWV with respect to the radio-sonde measurements in about the same degree. This leads to a good agreement of the FTIR and the AMSU-B measurements. The regression values for AMSU-B versus radio-sonde in Tables 1 and 3 differ within their standard deviation.

4 Variation of IWV above Ny Ålesund

In order to analyze the variation above Ny Ålesund, the RAM measurements are suited best because they are nearly continuous. The FTIR depends on sun or moon light and clear weather conditions.

In Fig. 5 a time series of RAM measurements of the IWV during February 2002 and in Fig. 6 a time series of RAM and FTIR measurements in the period of May 1999 is shown. Both plots contain the sonde measurements for comparison. During May 1999 the FTIR has been operated continuously whenever weather conditions permitted. The variation in the FTIR measurements being due to the changing sun zenith angle can be ruled out because the RAM measurements show the same variation.

Both figures, Figs. 5 and 6, clearly show the high variance of the IWV above Ny Ålesund. Even in clear weather it can easily be above 20% within a few hours.

The variance of IWV, as measured by the RAM, in time slots of 4 h, denoted by i, is shown in Fig. 7. For every slot i which contains more than 2 RAM measurements, the IWV is denoted by c_i^k, $k=1,...,n$. The variance in the ith bin, v_i, has been calculated by:

$$v_i = \frac{2\left(\max\left(c_i^k\right) - \min\left(c_i^k\right)\right)}{\max\left(c_i^k\right) + \min\left(c_i^k\right)} * 100. \quad (5)$$

The result shows that the change within 4 h is regularly more than 50%. The average of the variation in all time slots over all measurements is 30%.

5 Conclusions

In this work, four remote sensors are compared to IWV derived from radio sonde measurements. Due to changing weather conditions and the working principle of the sensors the time series of the measurements are only partially overlapping.

The microwave sensors, RAM and AMSU-B, operate best in winter, when the IWV is low. The infrared sensor, FTIR, depends on clear sight to the sun. The optical sensor SCIAMACHY also depends on solar light. Due to the short wave length of the radiation recorded by the SCIAMACHY instrument, clouds disturb the measurements considerably. This fact makes it necessary to cloud filter those measurements.

Measurements from three remote sensors (Solar-FTIR, SCIAMACHY, AMSU-B) can be considered of good quality. The higher variance of the satellite-based instruments may be explained by the spatial coverage and by the high variance of IWV. The Lunar-FTIR exhibits a low SNR and very sparse measurements. This may be an explanation for the high variance around the mean.

The solar FTIR measurements show the least scatter from the fitted line at all IWV-values and a very high correlation with the radio-sonde measurements. The satellite instruments yield IWV with a higher scatter. This may be explained by the high variability of water vapor around Ny Ålesund due to the topological structure of the island Spitsbergen.

Compared to the IWV derived from radio-sonde measurements, all instruments show a linear behavior, but measure somewhat lower IWV. The remote sensing instruments (SCIAMACHY, FTIR, AMSU-B, RAM) exploit different principles in order to derive the IWV. Nevertheless, a closer analysis with a cross correlation of the satellite measurements and FTIR and radio-sonde measurements points at a influence of the chosen subset of the SCIAMACHY measurements. The method of picking the subset suggests that clouds may be the problem.

From the comparison it becomes evident that there is no single instrument which is sufficient to measure the complete seasonal cycle with high time resolution of several measurements a day. Although radio-sondes could be launched very frequently, this is a prohibitive option in terms of waste and workload. A combination of the ground-based sensors is able to cover all seasons and ranges of IWV. The FTIR measures in sunlight and clear weather and also high IWV. The Lunar absorption measurements using the FTIR are very sparse and also rather noisy. The gap in the polar winter can however be filled using the microwave data from both instruments, the ground-based RAM and the satellite-based AMSU-B, which do not work above 50×10^{21} molec/cm^2 IWV and 30×10^{21} molec/cm^2 IWV, respectively.

Similar conclusions can be drawn for the satellite based instruments SCIAMACHY and AMSU-B. The strength of SCIAMACHY is the ability to measure high IWV but relies on solar irradiation of the atmosphere and on little interference by clouds. AMSU-B, however, does not rely on external irradiation of the atmosphere and delivers data throughout polar winter.

The measurements of the RAM are of fair quality. It has to be taken into account, however, that the RAM is not designed for measuring the IWV. The correlation between radio-sonde and RAM measurements proves that the data can be trusted. Even though the variance of the RAM measurements of IWV is high (about 30%), the measured variance of the IWV can be well above 100% within 4 h. This finding is supported by the measurement of the daily course of IWV using the FTIR instrument during May 1999.

By taking into account the fast changing IWV above Ny Ålesund, it cannot be expected that the comparison of the instruments is much better than in this work. Only the FTIR measurements have little variance. This can be understood by the specifics of the FTIR measurements which can only be performed during clear weather, when the conditions are stable.

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Table 1. Correlation of remote sensing measurements with radio-sonde measurements for the matching criteria as explained in Sect. 3.1. The radio-sonde measurements have been assumed with no error. The error for the remote sensors has been used as given by the analysis of those sensors.

Instrument	Nr. of Coincidences	Fitted line: Slope *m*	Fitted line: Offset *b* [10^{21} molec/cm^2]
FTIR Solar	136	0.85±0.01	2.2±0.3
FTIR Lunar	21	0.6±0.1	2.7±9.2
SCIAMACHY	304	0.73±0.03	3.4±0.83
AMSU-B	622	0.80±0.02	4.1±0.2
RAM	1043	0.91±0.01	−0.2±0.2

Table 2. Correlation of satellite instruments with FTIR data. This comparison hints at a cloud-bias for the IWV derived from SCIAMACHY measurements (for details Sect. 3.3.2).

Instrument	Nr. of Coincidences	Fitted line Slope b	Offset m [10^{21} molec/cm^2]
SCIAMACHY	86	1.31±0.02	−4.4±0.6
AMSU-B	236	1.00±0.03	2.2±0.5

Table 3. Correlation of satellite instruments with radio-sonde data for coincident measurements with FTIR and radio-sonde measurements.

Instrument	Nr. of Coincidences	Fitted line Slope	Offset [10^{21} molec/cm^2]
SCIAMACHY	12	1.09±0.07	−1.3±2.5
AMSU-B	50	0.86±0.04	4.4±0.9

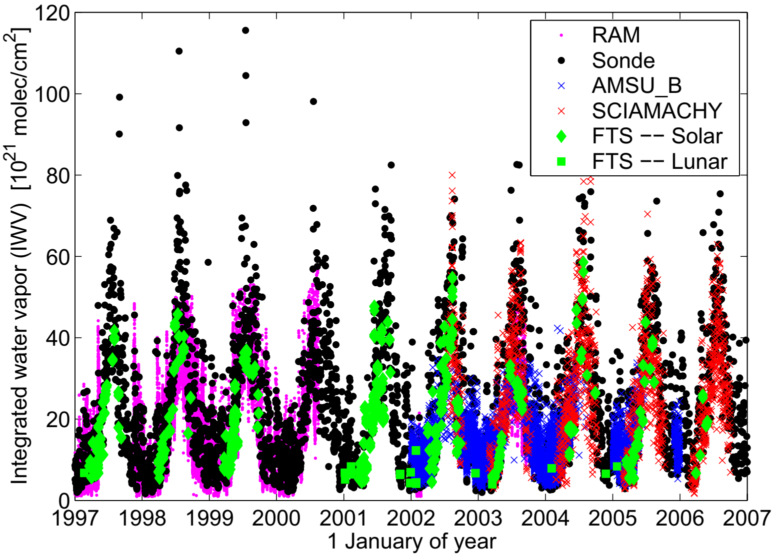

Fig. 1. Measurements of all remote sensors used in this work. All sensors capture the major features of IWV. The advantages and limitations of the remote sensors can readily be observed. While the microwave sensors AMSU-B and RAM are suited best to low IWV observed in polar winter, SCIAMACHY and FTIR depend on a cloud-free sky.

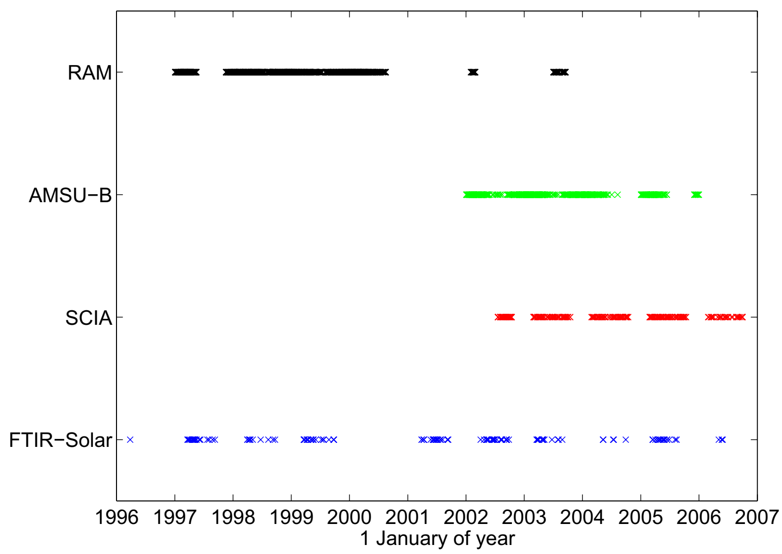

Fig. 2. Matches of the different instruments with radio-sondes during the years 1996 until 2007 for a time criterion of the time of the radio-sonde launch ±2 h. Every cross denotes one match. The radiosondes are launched every day.

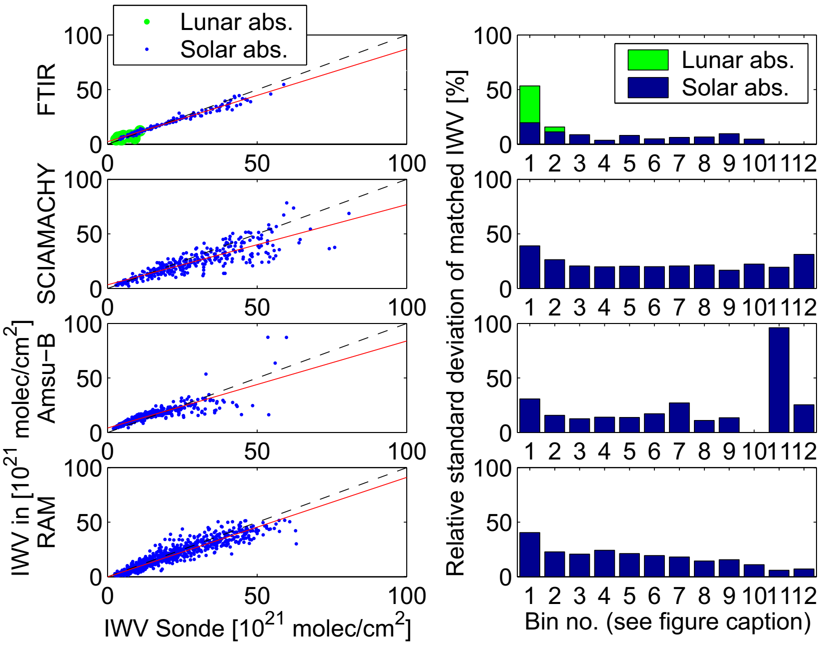

Fig. 3. Comparison of three remote sensing instruments. The plot on the left shows matching measurements (for matching criteria see Sect. 3.1) of the remote sensing instruments to IWV derived from radio-sondes. The black line is unity, the red line a fitted line. All values are in 10^{21} molec/cm^2. The plot on the right shows relative standard deviations of the remote sensing measurements to the fitted line. The bins are derived from the radio-sonde measurements. They are 5×10^{21} molec/cm^2 wide, starting at 0. The last bin is $55–60\times10^{21}$ molec/cm^2. The bars 10 to 12 for the AMSU-B measurements are invalid because of the very few measurements in this bins.

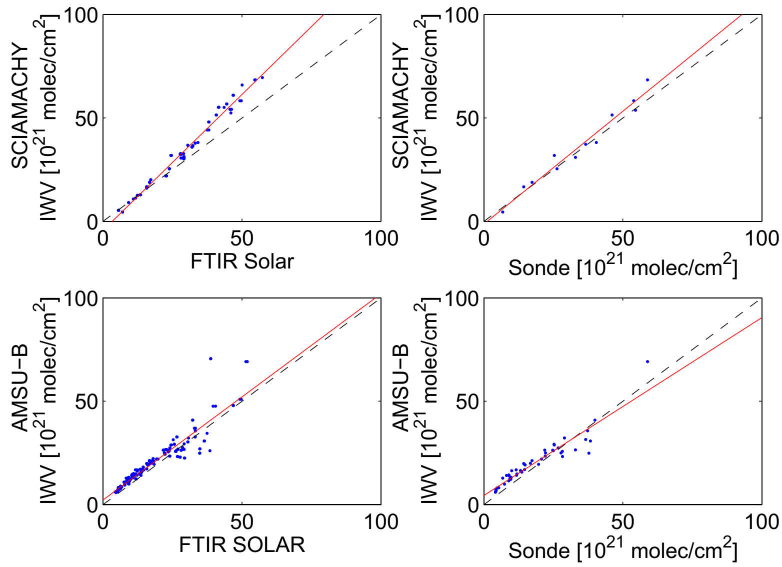

Fig. 4. Comparison of three remote sensing instruments to the results derived from FTIR measurements. The left column shows all coincident measurements from satellite and FTIR. The right panel shows the satellite measurements which coincide with FTIR measurements and radio-sonde measurements.

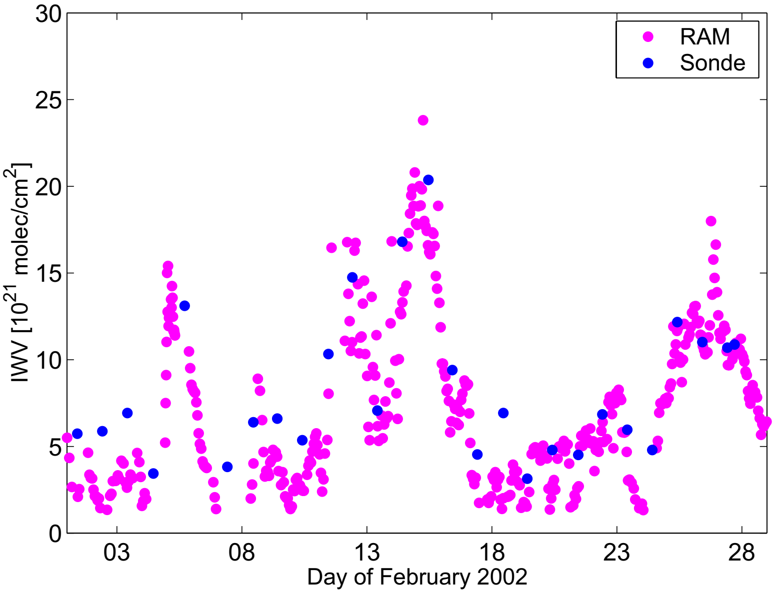

Fig. 5. Time series of RAM and radio-sonde measurements of IWV above Ny Ålesund in February 2002. Note: FTIR measurements are not available during the dark period above the Arctic.

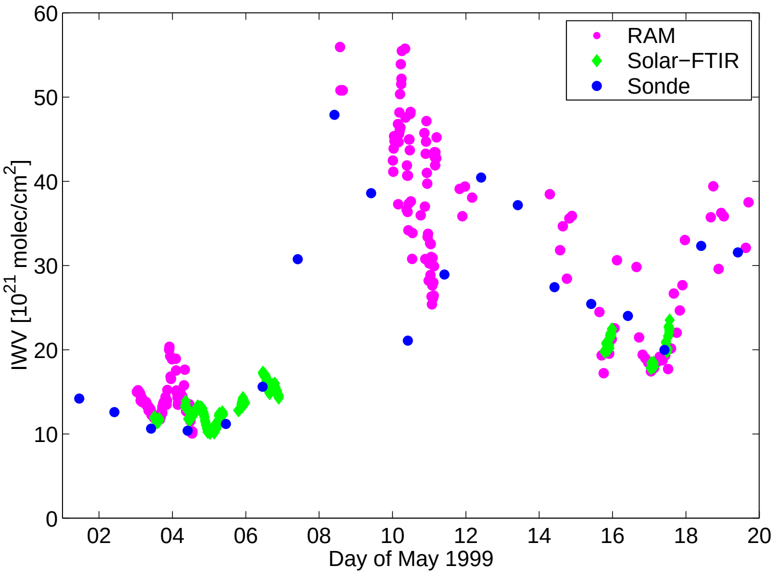

Fig. 6. Time series of RAM, radio-sonde and Solar-FTIR and RAM measurements above NY Ålesund in May 1999.

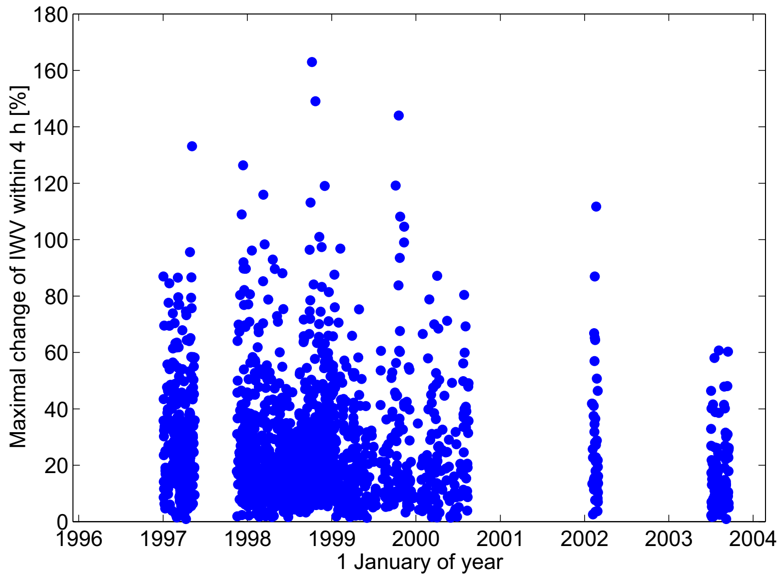

Fig. 7. The variance (maximum – minimum) in 4 h calculated from RAM measurements of IWV above Ny Ålesund.