EVALUATING SATELLITE RETRIEVALS OF INTEGRATED WATER VAPOUR DATA BY CO-LOCATED GROUND-BASED DEVICES FOR CLIMATE CHANGE ANALYSIS

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Abstract

Water vapour plays a dominant role in the climate change debate. However, observing water vapour for a climatological time period in a consistent and homogeneous manner is a challenging task. At one hand, homogenous networks of ground-based instruments retrieving Integrated Water Vapour (IWV) are being set up. Typical examples are Global Navigation Satellite System (GNSS) observation networks such as the International GNSS Service (IGS, Dow et al. [2005]), with continuous observations spanning over the last 15 years. On the other hand, satellite-based measurements of IWV by e.g. GOME, SCIAMACHY and GOME-2 are being merged in order to create long-term time series, or already have a time span of over 10 years (e.g. AIRS).

The aim of the present study is to set-up a techniques intercomparison of IWV measurements from satellite devices (in the visible, GOME/SCIAMACHY/GOME-2, and in the thermal infrared, AIRS) and from ground-based instruments (GNSS), in order to assess the applicability of either dataset for water vapour trends analysis. To this end, we selected about 30 sites worldwide at which the GNSS observations were directly compared with simultaneous satellite IWV observations. In particular, we analyse the impact of the presence of clouds and the distance between the satellite ground pixel centre and the co-located ground-based station on the agreement between satellite and ground-based retrievals of IWV. Furthermore, the geographical and seasonal variability of the properties of the IWV scatter plots between these different instruments are also investigated.

INTRODUCTION

The research described here is a part of a broader techniques intercomparison in which we compare the Integrated Water Vapour (IWV) measurements retrieved by 5 different techniques: 2 satellite devices (GOME/SCIAMACHY/GOME-2 and AIRS), 2 ground-based devices (GNSS and sun photometers), and 1 in-situ measurement technique (radiosondes). The ultimate goal of this study is to examine the capability of each technique to provide homogeneous, unbiased, long-term time series of IWV for climate change analysis. Here, we concentrate on the comparison of the two satellite-based IWV measurements with the IWV retrievals of co-located ground-based GPS (Global Positioning System) stations.

INSTRUMENTS AND DATASETS

For 28 northern hemisphere sites, shown in Figure 1, satellite overpass measurements are directly compared with the ground-based retrievals of IWV. The IWV datasets from the different instruments are retrieved as follows:

- **GPS**: the GPS-based Zenith Total Delay (ZTD) from the reprocessed and Final IGS troposphere products (Byun and Bar-Sever [2009, 2010]) is reduced into IWV by using surface measurements of temperature and pressure, gathered at synoptic stations at a horizontal distance of maximum 50 km from the GPS station (more details in e.g. Bevis et al. [1992], Saastamoinen [1972], Askne and Nordius [1987] and Davis et al. [1985]).
- **GOME/SCIAMACHY/GOME-2** (hereafter: **GOMESCIA**): the IWV is retrieved by applying the so-called Air Mass Corrected Differential Optical Absorption Spectroscopy method to nadir measurements from 608-680 nm (Wagner et al. [2011]).
- **AIRS**: the AIRS IWV is obtained by integrating the vertical profile of water vapour mixing ratio retrieved from cloud-cleared radiances in the range from 3.7 to 15 µm (Bedka et al. [2010], and references therein)

The advantages and disadvantages of each technique are summarized in Table 1.

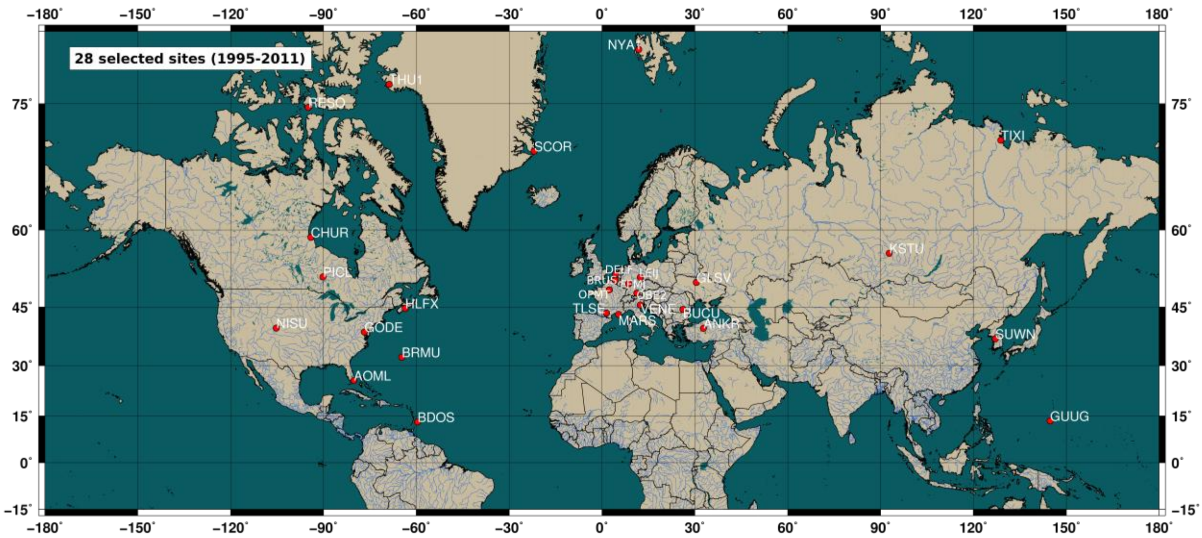

Figure 1: **Map of the selected IGS stations for comparison with satellite IWV retrievals**

	GPS	GOMESCIA	AIRS
spatial coverage	± 350 active IGS stations worldwide	global	global
spatial resolution	cone, with a radius of around 100 km at the tropopause	GOME: 40×320 km, SCIAMACHY: 30×60 km, GOME-2: 40×80 km	ellipsoidal, with major axis varying from 13.5 km (at nadir) to 31.5 km
temporal resolution	every 5 minutes	GOME, SCIAMACHY: max. once/day; GOME-2: max. twice/day *	maximum twice/day
temporal coverage	1995-now	1996-now	2002-now
all weather	yes	only if (almost) cloud free	only if (almost) cloud free
all directions	yes	nadir	nadir/limb

Table 1: **Main characteristics per technique**

SENSITIVITY ANALYSIS

For the evaluation of the satellite IWV measurements against ground-based retrievals, we should first define co-location and coincidence criteria, so that all overpass satellite measurements are reduced to a single overpass IWV value. This value will then be compared with the GPS IWV retrieval at that site and at that overpass time. For both AIRS and GOMESCIA, we imposed a maximum time interval of 30 minutes for comparison with GPS. Co-location is defined by a maximum distance of 50 km between the IGS station and the AIRS satellite ground pixel centre, and by demanding that the IGS station lies in the GOMESCIA ground pixel. We found that limiting the distance between the IGS station and satellite ground pixel centres gives rise to a better agreement between the techniques, although satellite cloud flag criteria are really necessary to obtain reasonable correlations. Therefore, we selected only AIRS data with the best cloud flag values (respectively 0 and 1 for a lowest good estimation of pressure equal to the surface pressure and lower than 300 hPa), and GOMESCIA measurements with normalized O_2 column densities larger than 1.

Next, we undertook a sensitivity analysis to study the impact of these selection criteria on the comparisons between satellite and GPS IWV retrievals. For instance, the effect of the cloud cover on the AIRS versus GPS agreement was studied by comparing for all co-locations the scatter plots of the samples with different cloud flag values. An example is given for the Brussels station in Figure 2. Similarly, for GOMESCIA, we compared the GPS-GOMESCIA scatter plots for samples with normalized O_2 absorption column densities lower or higher than the median value. For both satellites (see also Figure 2), we found that for higher cloud cover, the correlation coefficients with GPS decrease, the biases decrease (actually going from a wet bias to a dry bias), and the root mean squares (RMS) increase. Only for GOMESCIA, a higher cloud cover also led to lower regression slope coefficients.

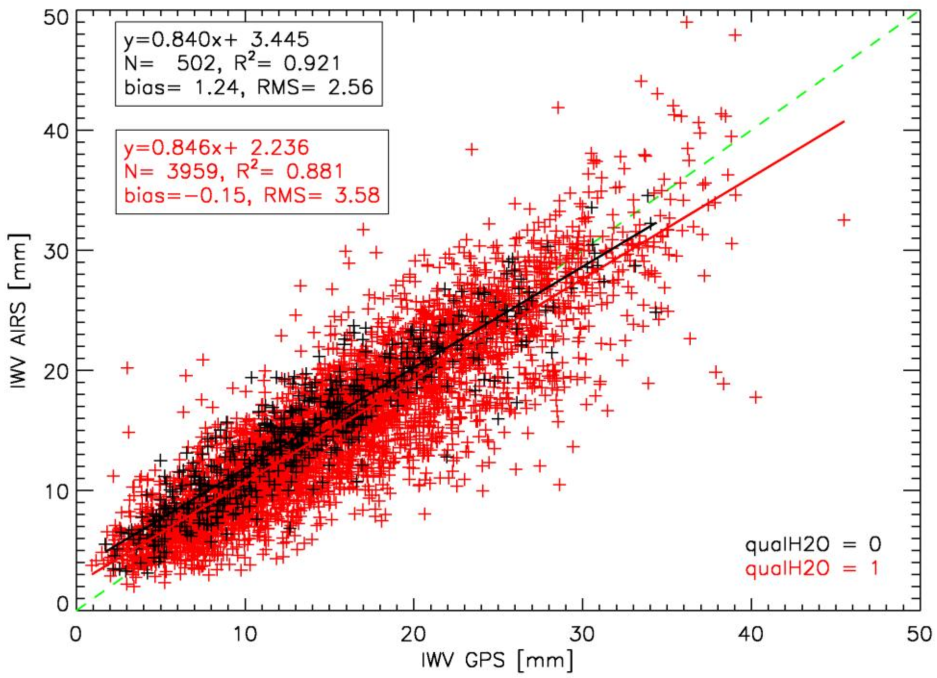

Figure 2: **Scatter plot of coincident IWV measurements of AIRS with the GPS device at Brussels, Belgium, for two different cloud quality flags of the AIRS IWV retrievals.**

We also looked at the internal consistency of the satellite IWV measurements by comparing them with the GPS retrievals. For AIRS, we found that the night-time retrievals show a better agreement with the GPS IWV values than the daytime retrievals (i.e. higher regression coefficients, lower RMS). The night-time retrievals show a positive bias, where the daytime measurements have a dry bias. On the other hand, the daytime retrievals have higher regression slopes with respect to the coincident and co-located GPS IWV values. Fetzer et al. [2005] found an absolute bias of 0.5 mm in the IWVs retrieved by AIRS and AMSR-E during night-time, but no bias during daytime observations. They attributed this daytime-night-time difference to increased stratus clouds at night which have deleterious effects on the AIRS retrievals. For GOMESCIA, we investigated whether or not it is feasible to merge the IWV measurements of those different satellite instruments into one dataset, as for example, large differences exits between the pixel sizes of those instruments (see Table 1). Therefore, we split the GOMESCIA dataset into the different instrument databases and compare these separately with the GPS IWV retrievals. The resulting scatter plots are presented here again for Brussels, in Figure 3. We can notice that the differences between the different scatter plots are not significant. This is in general also the case for the other stations we considered in our sample. Therefore, we can conclude that, for our purpose, the GOMESCIA retrieval method applied here (Wagner et al. [2011]), which makes use of instrument dependent offsets, leads to a homogenous IWV dataset.

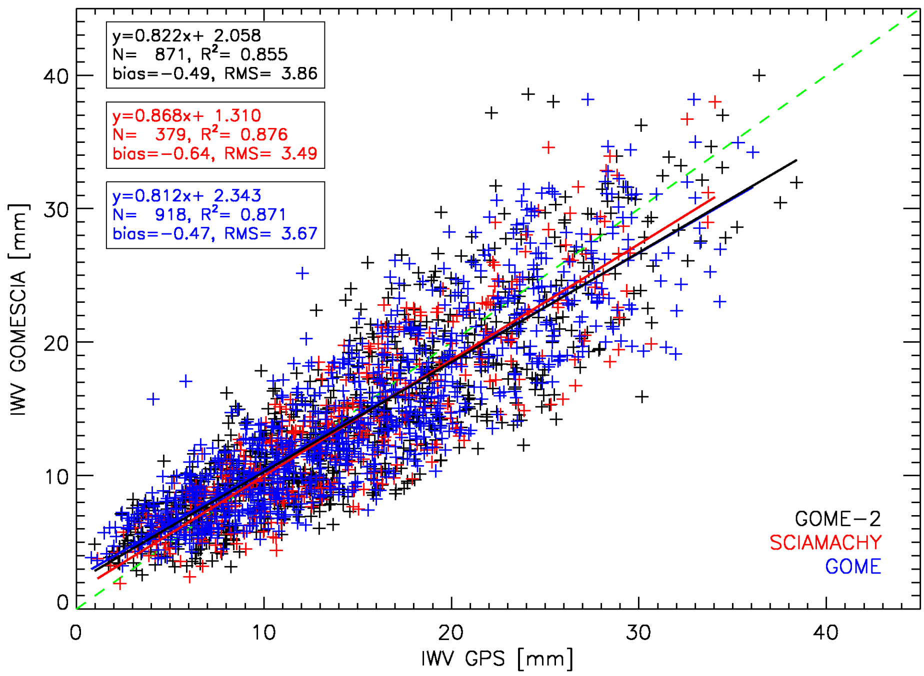

Figure 3: **Scatter plot of coincident IWV measurements of either GOME, SCIAMACHY, or GOME-2 with the GPS device at Brussels, Belgium.**

SPATIO-TEMPORAL VARIATIONS

Subsequently, we analysed the spatio-temporal variations of the GPS-satellite scatter plots. Therefore, we first sorted for the 28 co-locations the scatter plot properties (correlation coefficient, bias, RMS, regression slope coefficient) with latitude, longitude and GPS station height. The only clear geographical dependency that we could derive is a decreasing RMS with increasing latitude, as shown in Figure 4 for the GPS-AIRS co-locations.

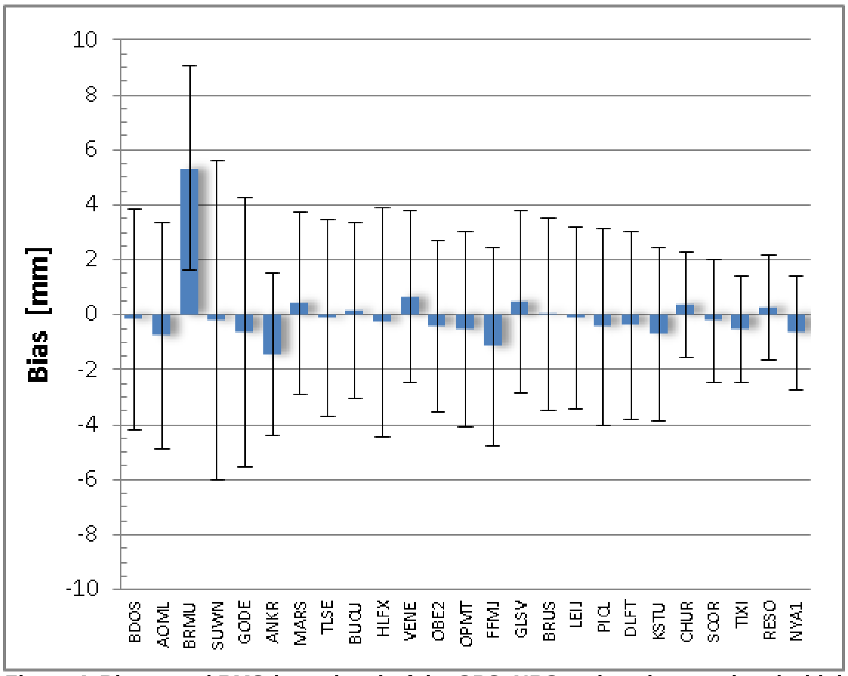

Figure 4: **Biases and RMS (error bars) of the GPS-AIRS co-locations, ordered with increasing latitude from the left to the right.**

Finally, the seasonal variation of the GPS-satellite scatter plot properties is analysed. In this case, both the bias and RMS show a clear seasonal, but opposite, variation: the GPS-satellite biases are minimal for maximum mean IWV (summer) and maximal for minimum mean IWV (winter), whereas the RMS is maximal for maximum mean IWV and minimal for minimum mean IWV (see Figures 5 and 6 for GOMESCIA). This latter finding is in agreement with the latitudinal variation of the RMS, because the higher the latitude, the lower the mean IWV. The seasonal behaviour of the bias might be explained by the fact that the satellite sensors and the GPS device seem to have different "sensitivities" at the IWV extremes: for the lower end range IWV values (occurring in winter), the satellite sensors measure higher IWV values than the GPS device gives (positive or large GPS-satellite biases). Oppositely, for the higher end range IWV values, the GPS retrieves higher IWV values than the satellite sensors, resulting in negative or small GPS-satellite biases. For the explanation of the seasonal and latitudinal variations of the GPS-satellite RMS, we follow the suggestion in Deblonde et al. [2005], that in the presence of strong humidity gradients (when moister air is involved) the location and sampling differences might be more significant and therefore give rise to higher RMS.

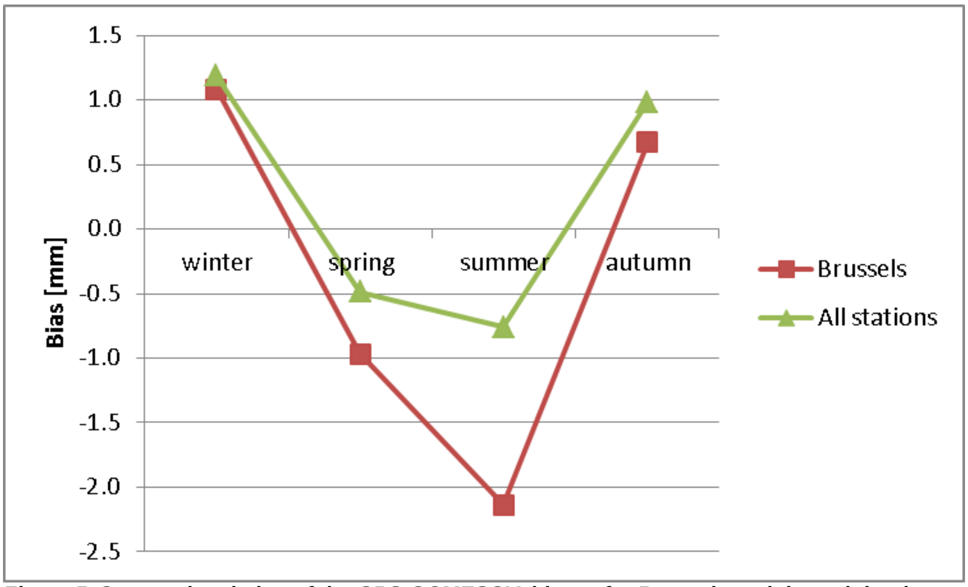

Figure 5: **Seasonal variation of the GPS-GOMESCIA biases for Brussels and the weighted mean biases of all stations (with weights equal to the number of coincident measurements per station).**

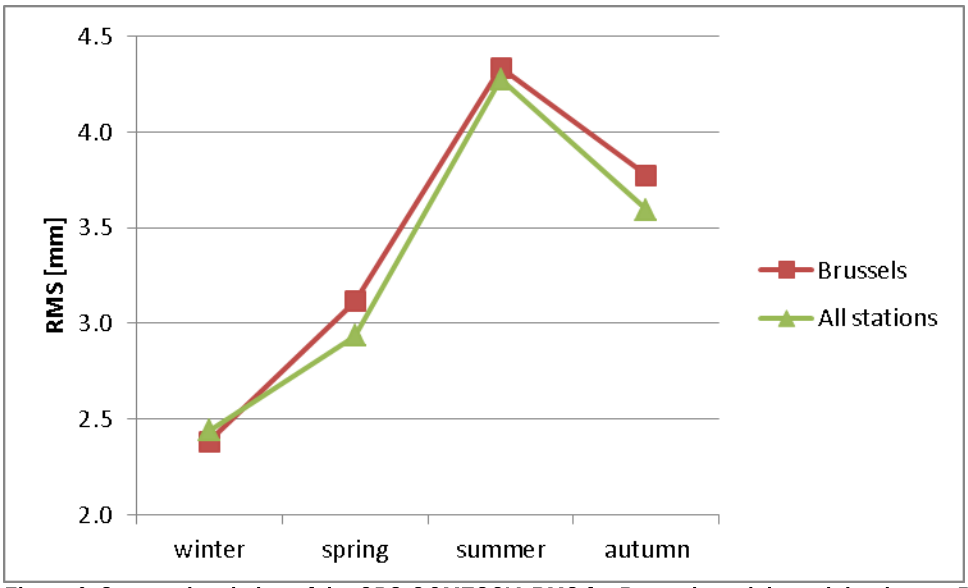

Figure 6: **Seasonal variation of the GPS-GOMESCIA RMS for Brussels and the weighted mean RMS of all stations (with weights equal to the number of coincident measurements per station).**

CONCLUSIONS

In this paper, we demonstrated that although originally tracing other slants or directions, and despite large differences in the projected ground areas, a good agreement between GPS and satellite IWV retrievals can be obtained. However, cloud cover is certainly an issue for the analysed satellite IWV retrievals; therefore, the use of cloud flag data is essential for improving the correlation with co-located GPS IWV values. Furthermore, we found differences between the daytime and night-time retrievals of AIRS IWV data, with the daytime retrievals generally comparing better with the GPS retrievals. We could also confirm that for the purpose of a comparison with co-located GPS data, it is feasible to treat the GOME, SCIAMACHY and GOME-2 retrievals as a merged, homogeneous dataset. Finally, only the RMS of the GPS-satellite IWV comparisons shows both a clear geographical and seasonal variability, which can be summarized as a positive correlation with the mean IWV value. We suggested that this is due to the fact that in the presence of strong humidity gradients (when moister air is involved) the location and sampling differences might be more significant.

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REFERENCES

Askne, J., and Nordius, H., (1987), Estimation of Tropospheric Delay for Microwaves from Surface Weather Data, Radio Sci., **22,** 3, pp 379-386

Bedka, S., Knuteson, R., Revercomb, H., Tobin, D., and Turner, D., (2010), An assessment of the absolute accuracy of the Atmospheric Infrared Sounder v5 precipitable water vapor product at tropical, midlatitude, and arctic ground-truth sites: September 2002 through August 2008, J. Geophys. Res., **115**, D17310, doi: 10.1029/2009JD013139

Bevis, M., Businger, S., Herring, T. A., Rocken, C., Anthes, R. A., and Ware, R. H., (1992), GPS meteorology: Remote sensing of atmospheric water vapor using the global positioning system, J. Geophys. Res., **97**(D14), pp 15787–15801, doi:10.1029/92JD01517

Byun, S. H. and Bar-Sever,Y. E., (2009), A new type of troposphere zenith path delay product of the international GNSS service, J. Geodesy, **83**, pp 367–373, doi: 10.1007/s00190-008-0288-8

Byun, S. H., and Bar-Sever, Y. E., (2010), The Re-Analysis of the IGS Tropospheric Product, IGS workshop, Newcastle, 28 June - 1 July 2010, available at: http://acc.igs.org/tropo/tropo-repro_IGSW10.pdf

Deblonde, G., Macpherson, S., Mireault, Y., and Heroux, P., (2005), Evaluation of GPS precipitable water over Canada and the IGS network, J. Appl. Meteorol., **44**, doi: 10.1175/JAM-2201.1, pp 153–166

Dow, J.M., Neilan, R.E., Gendt G., (2005), The International GPS Service (IGS): Celebrating the 10th Anniversary and Looking to the Next Decade, Adv. Space Res., **36,** (3), pp. 320-326, doi:10.1016/j.asr.2005.05.125

Davis, J. L., Herring, T. A., Shapiro, I. I., Rogers, A. E. E., and Elgered, G., (1985), Geodesy by Interferometry : Effects of Atmospheric Modeling Errors on Estimates of Baseline Length, Radio Sci., **20**, pp 1593-1607

Fetzer, E. J., Eldering, A., and Lee, S.-Y., (2005), Characterization of AIRS temperature and water vapor measurement capability using correlative observations, paper presented at the 85th Annual

Meeting of the Am. Meteorol. Soc., San Diego, California, 9-13 Jan. 2005, available at http://ams.confex.com/ams/pdfpapers/86552.pdf

Saastamoinen, J., (1972), Atmospheric correction for the troposphere and stratosphere in radio ranging of satellites, in: The Use of Artificial Satellites for Geodesy, Geophys. Monogr. Ser., **15**, edited by Henriksen, S. W., Mancini, A., and Chovitz, B. H., AGU, Washington, D.C., pp 247-251,

Wagner, T., Beirle, S. and Mies, K., (2011), Description of the MPI-Mainz H_2O retrieval (Version 5.0, March 2011), http://www.sciamachy.org/products/H2O/H2Ovc_IUP_AD.pdf