Evaluating the potential of integrated water vapour data from ground-based, in-situ and satellite-based observing techniques

R. Van Malderen[1], E. Pottiaux[2], H. Brenot[3], S. Beirle[4]

[1]Royal Meteorological Institute of Belgium, Ringlaan 3, B-1180 Brussels, Belgium
+32 2 373 05 95, Roeland.VanMalderen@meteo.be

[2]Royal Observatory of Belgium, Ringlaan 3, B-1180 Brussels, Belgium

[3]Belgian Institute of Space Aeronomy, Ringlaan 3, B-1180 Brussels, Belgium

[4]Max Planck Institute for Chemistry, Hahn-Meitner-Weg 1, 55128 Mainz,Germany

ABSTRACT

Water vapour plays a dominant role in the climate change debate. However, observing water vapour for climatological timescales in a consistent and homogeneous manner is challenging. To this end, Integrated Water Vapour (IWV) estimations derived from ground-based observations from Global Navigation Satellite Systems (GNSS) networks such as the International GNSS Service (IGS) network are very promising, with continuous observations spanning over the last 15+ years. Also, the AErosol RObotic NETwork (AERONET) provides long-term and continuous ground-based observations of the IVW performed with standardized and well-calibrated sun photometers.

The aim of the present study is to assess the applicability of either dataset for water vapour time series analysis. Therefore, we compare IWV values retrieved (at zenith) from these two techniques, focusing on a selection of 28 sites located worldwide. We show that both techniques agree at the level of -0.26 mm +/- 1.41 mm of IWV. In a case study at the station Uccle (Brussels, Belgium), we further investigate the influence of the clouds on the IWV inter-technique comparison.

Additionally, for our selection of 28 sites, we compare the GNSS and sun photometer IWV values with simultaneous and co-located radiosonde and satellite-based IWV measurements (GOME/SCIAMACHY/GOME-2). In particular, we investigate the geographical dependency of the properties of the IWV scatter plots between all these different instruments.

1 Introduction

Water vapour is a key variable for climate research. It is the dominant greenhouse gas in the atmosphere and provides the largest known feedback mechanism for amplifying climate change. The knowledge of the temporal and spatial variability of water vapour is of major importance to understand and predict any change in our climate system. Radiosondes have been widely used in the literature to assess the trends in the Integrated Water Vapour (IWV), although these datasets suffer from large inhomogeneities due to humidity sensor improvements between different types of radiosondes (e.g. Van Malderen and De Backer [2010]). The major advantage of radiosonde measurements is their long temporal coverage. Looking for homogeneous datasets of IWV with increasing time coverage, networks of ground-based Global Navigation Satellite Systems (GNSS) receivers (such as the International GNSS Service (IGS) network) or sun photometers (the Aerosol Robotic NETwork (AERONET)) provide very promising estimations of the IWV. Also databases obtained by merging adequately satellite retrievals (e.g. from GOME, SCIAMACHY and GOME-2 instruments) are extending over more than 15 years and moreover, offer a global spatial coverage.

In this paper, we examine the capability of each technique to generate homogeneous, unbiased, and long-term IWV time series by comparing simultaneous measurements at co-located sites.

2 Instruments and datasets

Within a maximum separating distance of 30 km, 28 co-locations are found worldwide between IGS GNSS sites and AERONET CIMEL sun photometer locations (see **Figure 1**). Additionally, we looked for radiosonde launches and GOME, SCIAMACHY and GOME-2 crossings at those selected sites. The IWV datasets from the different instruments are retrieved as follows:

- **GNSS**: 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 GNSS station (more details in e.g. Bevis et al. [1992], Saastamoinen [1972], Askne and Nordius [1987] and Davis et al. [1985]).
- **CIMEL**: the IWV is obtained by measuring the (direct) sun radiance at a 940 nm channel (centred on the 946 nm water vapour absorption line).
- **Radiosondes**: the IWV is calculated through integration of the vertical profiles of temperature and relative humidity.
- **GOME/SCIAMACHY/GOME-2**: the IWV is retrieved by applying the so-called Air Mass Corrected Differential Optical Absorption Spectroscopy method to nadir measurements around 700 nm.

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

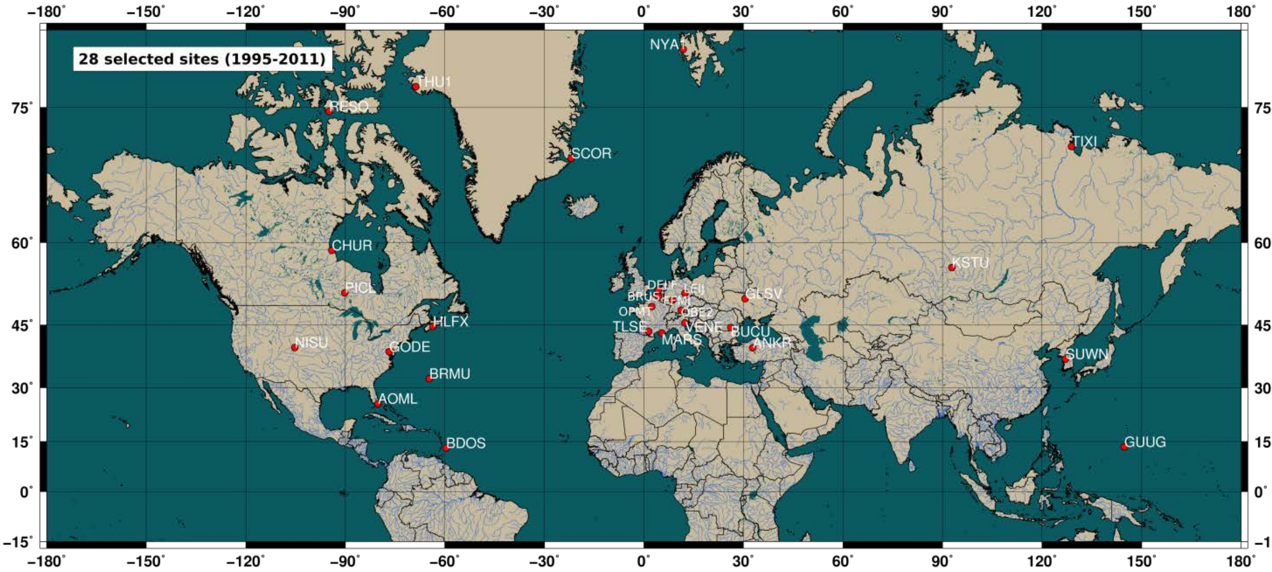

Figure 1: Map of the selected IGS sites that are co-located with at least one of the CIMEL or radiosonde instruments.

Technique	Spatial coverage	Temporal resolution	Time span	All weather/All direction
GNSS	± 350 IGS sites	every 5 minutes	1995-now	yes/yes
radiosonde	± 1500 IGRA sites	on average twice/day	1950s-now	yes/vertical profile
CIMEL sun photometer	± 300 AERONET sites	± 15 min, depending on weather conditions	1993-now	clear sky only/solar direction
GOME/GOME-2/ SCIAMACHY	global	maximum once/day	1996-now	only if (almost) cloud free/nadir

Table 1: Main characteristics for each technique.

3 Methodology

From the discussions of the different techniques and IWV datasets in section 2 (and in e.g. Elgered et al. [2005]), it is clear that the GNSS technique has the largest potential to be used for IWV trend analyses in the context of climate change. Indeed, GNSS is the only technique than can provide at the moment a long-term, worldwide, homogeneously (re)processed and all-weather database of IWV values at a high temporal resolution. For this reason, we selected in this paper the IWV dataset derived from the IGS GNSS network as the reference to which the observations of all other co-located techniques will be compared.

We also chose to compare only simultaneous measurements. This has to be interpreted in the strictest sense, because we did not apply any time averaging nor any interpolation. Instead, all comparisons shown are point-by-point comparisons, which means that every IWV measurement of a given instrument (not GNSS) will be compared with the corresponding GNSS IWV value, within a maximal time interval of 10 minutes for the CIMEL instrument, and 30 minutes for radiosondes and GOME/SCIAMACHY/GOME-2.

It should be noted that there might exist an altitude difference between the different co-located ground-based or in-situ instruments measuring the IWV. This altitude difference will introduce at least an artificial bias between the IWV datasets gathered with different techniques, because the device that is located at the lower altitude should logically measure a larger column of water vapour, and hence larger IWV values. However, after exploring the possibilities of applying inter-technique altitude difference correction schemes and investigating their impact on the inter-technique comparisons, we decided to apply only on the radiosonde measurements an altitude difference correction with respect to the co-located GNSS device.

4 Case study: the Uccle station

To demonstrate the methodology used for the inter-technique comparison, we first focus on the IWV databases gathered at Uccle, Brussels, Belgium (IGS station BRUS, 50°48'N, 4°21'E, 100 m asl.). We have several reasons to concentrate first on this IGS station. First, all ground-based instruments used in this study are exactly co-located at the same site at Uccle. This is also the case for the weather station providing the necessary meteorological data, at high temporal resolution (10 minutes) for the ZTD to IWV reduction. So, for Uccle we do not have to take into account any height difference nor separation distance between the different instruments! Secondly, several meteorological data (e.g. the cloud cover) collected at Uccle (location of the Royal Meteorological Institute of Belgium) provide additional information for the interpretation of IWV differences between different instruments: these can e.g. clarify if meteorological conditions have an impact on the performances of the different datasets. Thirdly, we dispose of all metadata of each of the ground-based and in-situ devices operated in Uccle, so that we are aware of any instrumental change that might give rise to an inhomogeneity in the instrument's IWV time series.

The IWV scatter plots of the different devices with respect to the GNSS reference are shown in **Figure 2.** The mean bias between the different techniques varies between -0.6 mm (GOME/SCIAMACHY/GOME-2) to 0.6 mm (RS9x). The best correlation and lowest dispersion of the data points are reached for the CIMEL versus GNSS comparison, which confirms our early assumption about the data quality of both datasets. It could also be noted that IWV values from Vaisala’s state-of-the-art radiosonde types (RS9x) compares better with regard to the GNSS than the preceding RS80 type. An another interesting feature is that the slopes of regression lines with respect to the GNSS device are closer to 1 for the other all-weather device (radiosondes) than for instruments demanding a partly clear sky (i.e. the CIMEL, GOME/SCIAMACHY/GOME-2 devices).

We elaborated more on this last point for the CIMEL measurements. Therefore, we analysed the CIMEL-GNSS scatter plot properties for different types of cloudiness, observed at Uccle. First of all, it should be noted that the (mean) IWV value observed by both the CIMEL and the GNSS increase with increasing cloud cover. This is of course intuitively expected, but is confirmed by our analysis. Secondly, the average IWV value observed by GNSS increase stronger with increasing cloud cover than the CIMEL average IWV does. Or to put it differently, for increasing cloud cover, GNSS is measuring more frequently high IWV values than the CIMEL sun photometer does. We believe that this is due to the fact that under such meteorological conditions, (zenith) IWV values observed by GNSS are incorporating contributions from clouds while observing in slant directions towards the different satellites. The CIMEL observation on the other hand, is always a cloud-free measurement in the solar direction solely. Thus, the only contribution from clouds might be in the air mass measurement, needed to convert the solar slant measurements to the zenith values. As a consequence, the higher range of GNSS IWVs for more cloudy skies give rise to lower regression line slope coefficients of the CIMEL-GNSS scatter plots, caused by the observation bias of the CIMEL instrument.

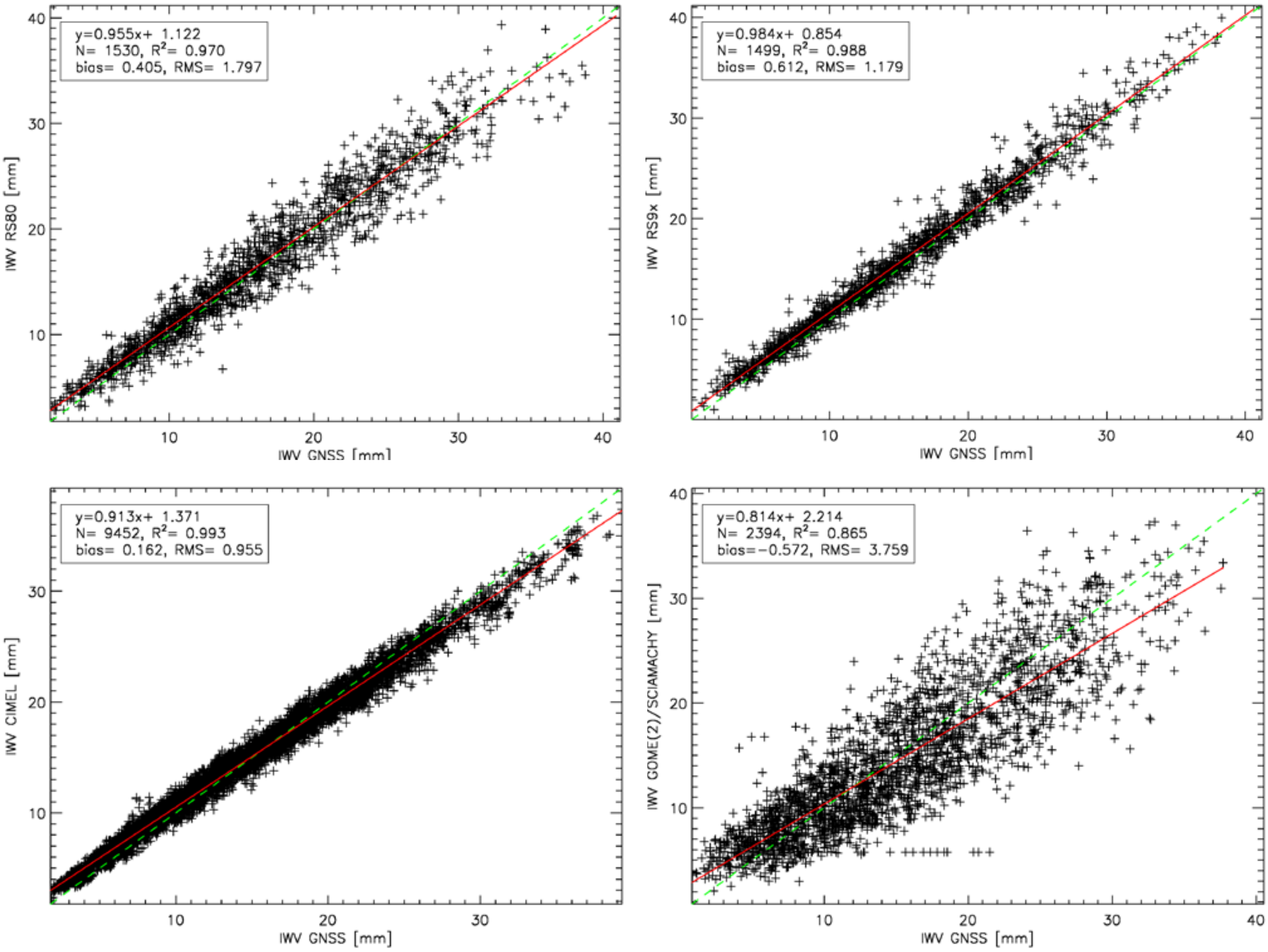

Figure 2: Scatter plots of simultaneous IWV measurements of the different instruments with the GNSS device. The upper plots are for the radiosondes, but separated for each radiosonde type: Vaisala RS80 in the left panel, Vaisala RS90 and RS92 (= RS9x) in the right panel.

5 Worldwide exploitation of the IWV dataset

In a second step, we extended our inter-technique comparison study worldwide. We created scatter plots similar to **Figure 2** for the selected 28 IGS sites for which we found instrumental co-location. Results are summarised in **Figure 3** and **Figure 4**. A first important conclusion to draw is that the IWV values from the CIMEL instrument compare best with those of the GNSS technique, because the scatter plots show the best correlations and the lowest scatter. Hence, both ground-based devices provide datasets that could be used to study IWV tendencies, as long as the data homogeneity can be further guaranteed. It should however be mentioned that all slopes of the CIMEL to GNSS regression lines are smaller than 1, due to the observation bias of the CIMEL instrument: it measures only when the sky is clear and solely in the solar direction. Moreover, significant differences exist between the regression slopes at sites where different CIMEL sun photometers can be compared with one IGS GNSS station (e.g. BRMU, NISU, TLSE, BUCU, VENE, OBE2, and OPMT). As the different sun photometers in the AERONET network should be calibrated on a regular basis against a standard photometer, instrumental differences should theoretically be ruled out as the cause for these differences with respect to the GNSS devices. On the other hand, geographical differences between each of the CIMEL sites might influence the comparisons of these instruments with the same IGS station.

In general, there is neither a clear latitudinal nor a longitudinal dependency of the scatter plots properties. The GOME/SCIAMACHY/GOME-2 IWV observations show the largest (but apparently) random geographical variability relative to the co-located GNSS IWVs, which could partly be explained by the poorer correlations obtained between both datasets. The mean of the regression slopes is also significantly below 1, reflecting the fact that almost cloud free conditions are needed to perform those satellite-based nadir measurements.

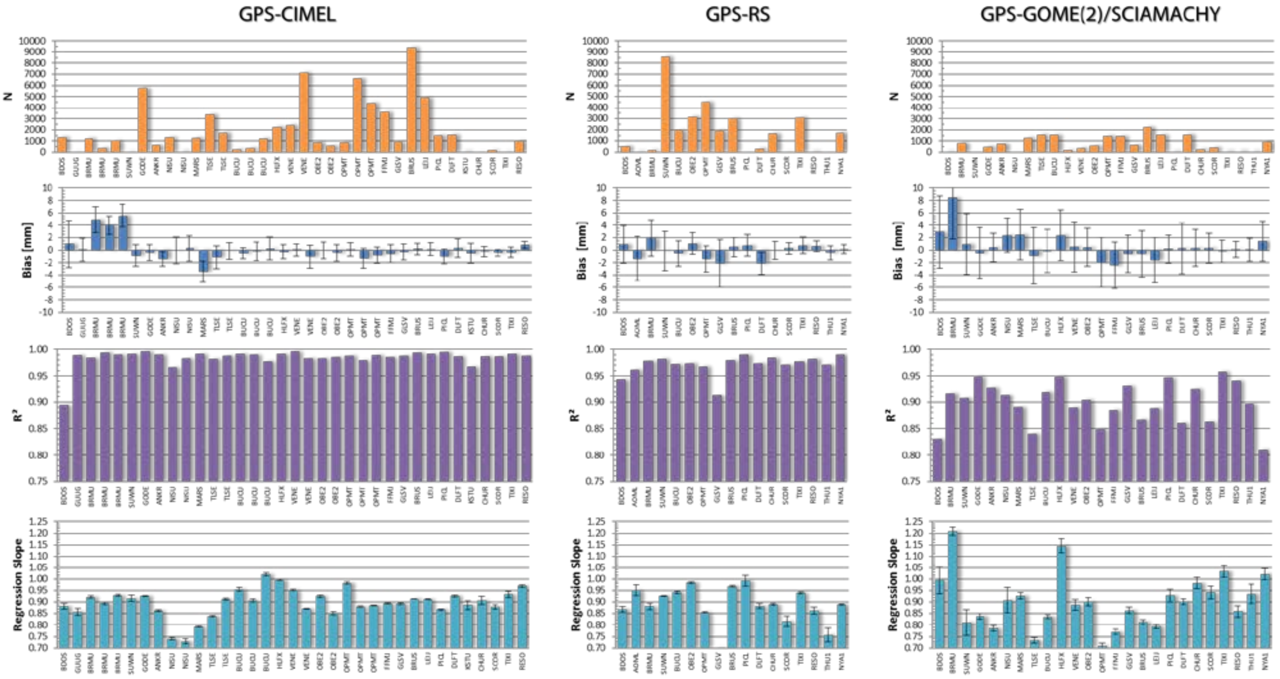

Figure 3: Column bar plots of scatter plot properties (count N, bias, R² and regression slope) of the different instruments versus GNSS for the selected sites worldwide. Sites are ordered with increasing latitude. The errors represent the RMS (bias) and the standard deviation (regression slope).

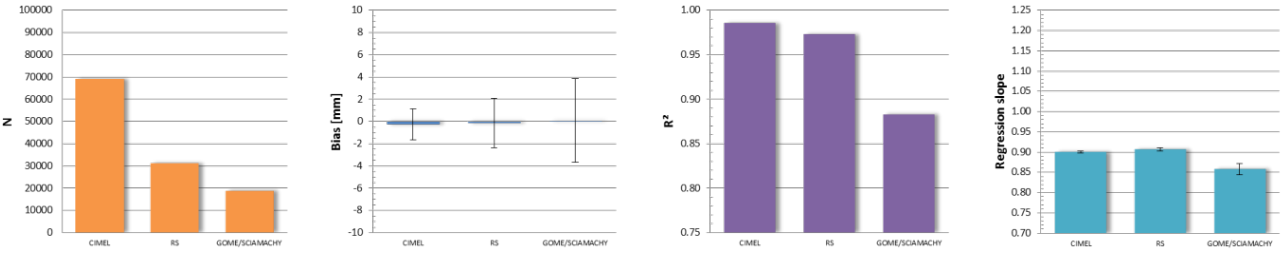

Figure 4: Column bar plots of scatter plot properties (count N, bias, R² and regression slope) of the different instruments versus GNSS averaged over all stations included in the inter-technique comparison. Error bars: see **Figure 3**.

Given the fact that for the different radiosonde sites, the data are obtained from different radiosonde types (with different properties for the humidity sensors) and merged for the comparison with the co-located GNSS device, the correlation between both IWV data sources is very satisfactory. The mean of the slopes of the radiosonde to GNSS regression lines is the highest (see **Figure 4**), compared to the CIMEL and the satellite-based data, which can be attributed to the fact that radiosondes are operating under all weather conditions, as the GNSS devices do.

6 Conclusions and perspectives

Both studied ground-based instruments measuring the Integrated Water Vapour (IWV), namely the sun photometer (belonging to the AERONET network) and the GNSS (belonging to the IGS network) devices, have the potential to build up IWV time series that can be used to study trends within the framework of climate change. The homogeneity of the data processing and the instrumental calibration are major advantages of these networks. As seen in **Figure 3**, IWV values from both instruments show a very good agreement. To which extent the observation bias of the CIMEL instrument (a clear sky in the solar direction is needed) can have an impact on the IWV trends, is the subject of a follow-up study.

A lot of effort has been undertaken to homogenize the IWV data measured by 3 different UV/VIS sensors on-board polar orbiting satellites: GOME, SCIAMACHY and GOME-2. The agreement of this dataset with the GNSS instruments for our selection of stations is very promising and we look forward to compare the IWV trends calculated for both datasets.

Acknowledgments

This research has been carried out in the framework of the Solar-Terrestrial Centre of Excellence (STCE). The authors are grateful to all colleagues and data providers having participated in this study. A particular thanks goes to the IGS and the AERONET for their excellent network management making such research possible.

References

Askne, J. and Nordius, H. (1987), Estimation of tropospheric delay for microwaves from surface weather data, Radio Science, 22:379-386.

Bevis, M., S. Businger, T. A. Herring, C. Rocken, R. A. Anthes, and R.Ware (1992), GPS meteorology: Remote sensing of atmospheric water vapor using the Global Positioning System, J. Geophys. Res., 97(D14), 15787–15801.

Byun, S. H., and Bar-Sever, Y. E. (2009), A new type of troposphere zenith path delay product of the international GNSS service. Journal of Geodesy, 83(3-4), pp.1-7.

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

Davis, J. L., Herring, T. A., Shapiro, I. I., Rogers, A. E. E., and Elgered, G. (1985), Geodesy by radio interferometry: effects of atmospheric modelling errors on estimates of baseline length, Radio Science, 20(6):1593–1607.

Elgered, G., H.-P. Plag, H. van der Marel, S. Barlag, & J. Nash (eds.), COST 716: Exploitation of ground-based GPS for climate and numerical weather prediction applications, Final Report, European Community, EUR 21639, ISBN 92-898-0012-7, 2005.

Saastamoinen, J. (1972), Atmospheric correction for troposphere and stratosphere in radio ranging of satellites. The Use of Artificial Satellites for Geodesy, Third International Symposium on The Use of Artificial Satellites for Geodesy.

Van Malderen, R., and H. De Backer, A drop in upper tropospheric humidity in autumn 2001, as derived from radiosonde measurements at Uccle, Belgium, J. Geophys. Res., 115, D20114, doi:10.1029/2009JD013587, 2010.