LONG-TERM TRENDS IN THE AMOUNT OF ATMOSPHERIC WATER VAPOUR DERIVED FROM SPACE GEODETIC AND REMOTE SENSING TECHNIQUES

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ABSTRACT

We present long term trends in the amount of atmospheric water vapor at the Swedish West Coast derived from four different techniques. Three of the techniques, geodetic Very Long Baseline Interferometry (VLBI), GPS and ground-based microwave radiometry, are co-located at the the Onsala Space Observatory, while the fourth technique, radiosondes, is operated at Gothenburg-Landvetter Airport in about 37 km distance to Onsala. The time series cover up to 30 years of data. The four techniques detect individual positive trends in the integrated water vapor (IWV) on the order of 0.3 to 0.6 kg/m^2 per decade. The IWV data derived from the techniques have correlation coefficients on the order of 0.95 and better and root-mean-square differences of less than x.x. However, there is no perfect agreement between the IWV trends derived by the four techniques, which partly might be explained by different temporal sampling and data gaps.

Key words: Integrated water vapor, geodetic VLBI, GPS, microwave radiometry, radiosondes.

1. INTRODUCTION

Both science and society are interested in the amount of atmospheric water vapour and its temporal and spatial variations. Science needs long and consistent time series of integrated water vapour (IWV) to improve meteorological and climatological models. In turn, society is interested in these models because of anthropogenically influenced climate change scenarios.
There are various techniques that are sensitive to IWV and can be used to monitor IPWV variations. A traditional technique measurement device for upper air observations in meteorology are radiosondes, and long-term IWV trends from radiosonde observations have been presented e.g. by Gaffen et al. (1992). Also ground-based microwave radiometry observations have been used to determine IWV-trends Elgered & Jarlemark (1998). During the last years the potential of space geodetic techniques has been exploited to monitor IWV and results based on Very Long Baseline Interferometry (VLBI) e.g. Herring et al. (1990), Heinkelmann et al. (2007), and also results based on GPS data analysis, e.g. Tralli & Lichten (1990) Emardson et al. (1998), Gradinarsky et al. (2002), Elgered et al. (2005), Nilsson & Elgered (2008), have been presented.
The individual techniques have technique specific advantages and disadvantages in terms of instrumental stability, measurement uncertainty, temporal and spatial sampling. Therefore a comparison of the results derived from co-located sensors is of particular interest. To address these issues, We focus on the data obtained with different co-located techniques operated at the Onsala Space Observatory at the Swedish west coast. The observatory hosts co-located equipment for geodetic VLBI, ground-based microwave radiometry and GPS. Data for more than three decades have been collected with these two of the techniques. Additionally, in about 37 km distance to the observatory radiosondes are launched at the Gothenburg-Landvetter Airport since more than three decades.

2. OBSERVATIONS AND DATA ANALYSIS

2.1. Radiosondes

Radiosondes (RS) are a traditional measurement device for upper air observations in meteorology. The Swedish Meteorological and Hydrological Institute (SMHI) launches RS at a couple of sites in Sweden, and the closest radio launch station to the Onsala Space Observatory is at the Gothenburg-Landvetter airport. RS have a long and continuous observation history, but the launching interval has varied over the years between 6, 12 and 24 hours. Also the type of RS has changed over the years. Before March 1986 the RS type Vaisala RS18 was launched. Starting in December 1985 the RS type Vaisala RS80 was in use, and both types were used in parallel during an overlapping period of four months. Since February 2006 the RS type Vaisala RS92 is utilized.

RS data are available as atmospheric profiles of pressure, temperature, and humidity. These profiles were analyzed using the in-house developed CalcRS software, and finally IWV results were derived. Based on measurement accuracies of the sensors used in the RS England et al. (1993), the IWV accuracy is assumed to be 5% of the absolute value.

2.2. VLBI

The Onsala Space Observatory is actively contributing to high quality geodetic VLBI observations since the 1980'ies (Scherneck, 1998). On average, about 20 to 30 individual VLBI sessions of 24 hour duration are performed every year at Onsala. Additionally, a number of continuous campaigns have been observed, covering up to 15 days. A global VLBI data set was analyzed covering January 1984 to the end of 2010 using the CALC/SOLVE software Ma et al. (1990). The necessary no-net-translation and no-net-rotation constraints were applied and the NMF mapping functions Niell (1996) were used. A large number of parameters were determined in the analysis. Station positions and velocities were estimated as global parameters, and earth rotation and orientation parameters as daily parameters. Relative clock parameters and local Zenith Wet Delay (ZWD) parameters were estimated as piece-wise linear functions with a 1 h resolution, and Horizontal Delay Gradients (HDG) as piece-wise linear functions with a 3 h resolution. The VLBI data analysis software uses data of the local pressure sensor to calculate Zenith Hydrostatic Delay (ZHD) values. The local pressure sensor at Onsala is located 12.7 m below the VLBI reference point. This implies that the estimated ZWD values are underestimated and need to be corrected. A correction of 3.6 mm was therefore added to the ZWD time series. This correction is accurate to ± 0.4 mm for a usual range of pressure and temperature variation at Onsala, which is much smaller than the formal error of the ZWD values derived from VLBI. After this correction the ZWD time series was converted to IWV following the seasonal and station dependent formalism described in Emardson & Derks (2000).

An obvious disadvantage of the VLBI technique is that the observing sessions at Onsala are unfortunately not on regular intervals and thus the amount of atmospheric water vapor is not sampled regularly at Onsala with VLBI. On the other hand does the VLBI techniques promise long term stability due to its stable instrumentation.

2.3. WVR

The Onsala Space Observatory performs microwave radiometry measurements since 1980 Elgered et al. (1991) using a so-called water vapor radiometer (WVR). This instrument has two microwave channels for 21.0 GHz and 31.4 GHz with horn antennas with an opening angle of 6 degrees. Before 1993 the instrument was mainly operated only during VLBI observations but since 1993 it is used almost continuously in a so-called sky-mapping mode. This operation mode means that the local sky is repeatedly monitored by observations of the sky brightness temperature in a number of azimuth and elevation directions. A full observation cycle takes about 15 minutes. The instrument was repaired and upgraded several times since 1980. This caused periods in 1991/1992, 2003 and 2006/2007, respectively, when the instrument unfortunately was not operating and no data were recorded.

The acquired WVR-data were analyzed using the in-house developed RadGrad software and zenith wet delays and gradients were estimated with a temporal resolution of 30 minutes. The ZWD results were then converted to IWV as described before.

2.4. GPS

The Onsala Space Observatory operates a GPS station that is part of the Swedish Permanent GPS Network SWEPOS and contributes to the International GNSS Service (IGS). Since 1993 the station is operated continuously, before that it was operated on campaign basis. During the years there were a number of instrumentation changes, mainly receiver changes, but also a change of the radome covering the GPS-antenna. Until the end of January 1999 a conical radome was used and since February 1st, 1999 then a hemispherical radome is in use.

GPS-data from November 1996 to the end of 2010 were analyzed with the Gipsy-Oasis-II software (Webb & Zumberge, 1993) version 5 using the Precise Point Positioning (PPP) strategy (Zumberge et al., 1993). The reprocessing products for GPS orbit and clock products provided by the Jet Propulsion Laboratory were used for the data analysis. Absolute calibration of the Phase Centre Variations (PCV) was implemented in the data processing and the NMF mapping functions Niell (1996) were used. Station coordinates, clock biases, and tropospheric parameters were estimated. This provided time series of zenith total delays (ZTD) with a temporal resolution of 5 minutes. Since the Gipsy-Oasis-II software uses station dependent constant apriori values for the ZTD a post-processing step is needed to derive ZWD. Based on pressure data derived from the ECMWF re-analysis product ZHD values were calculated and subtracted from the ZTD to give ZWD. The ZWD results were then converted to IWV as described before. Since the data set has a very high temporal resolution of 5 minutes, it was re-sampled to a 1 hour temporal resolution.

3. COMPARISON OF IWV TIME SERIES

The time series of IWV derived from RS, VLBI, WVR and GPS data analysis are presented in Fig. 1. The RS and GPS derived IWV time series is most regularly sampled, while both the VLBI and WVR derived IPWV time series have several data gaps. The GPS derived IWV time series is considerably shorter than the other three time series. Seasonal signatures are clearly visible in all four time series and a seasonal model that includes six parameters (offset, rate, cosine and sine amplitudes of an annual and a semi-annual period) can be fitted independently to each data set. Table 1 shows the derived IWV trends.

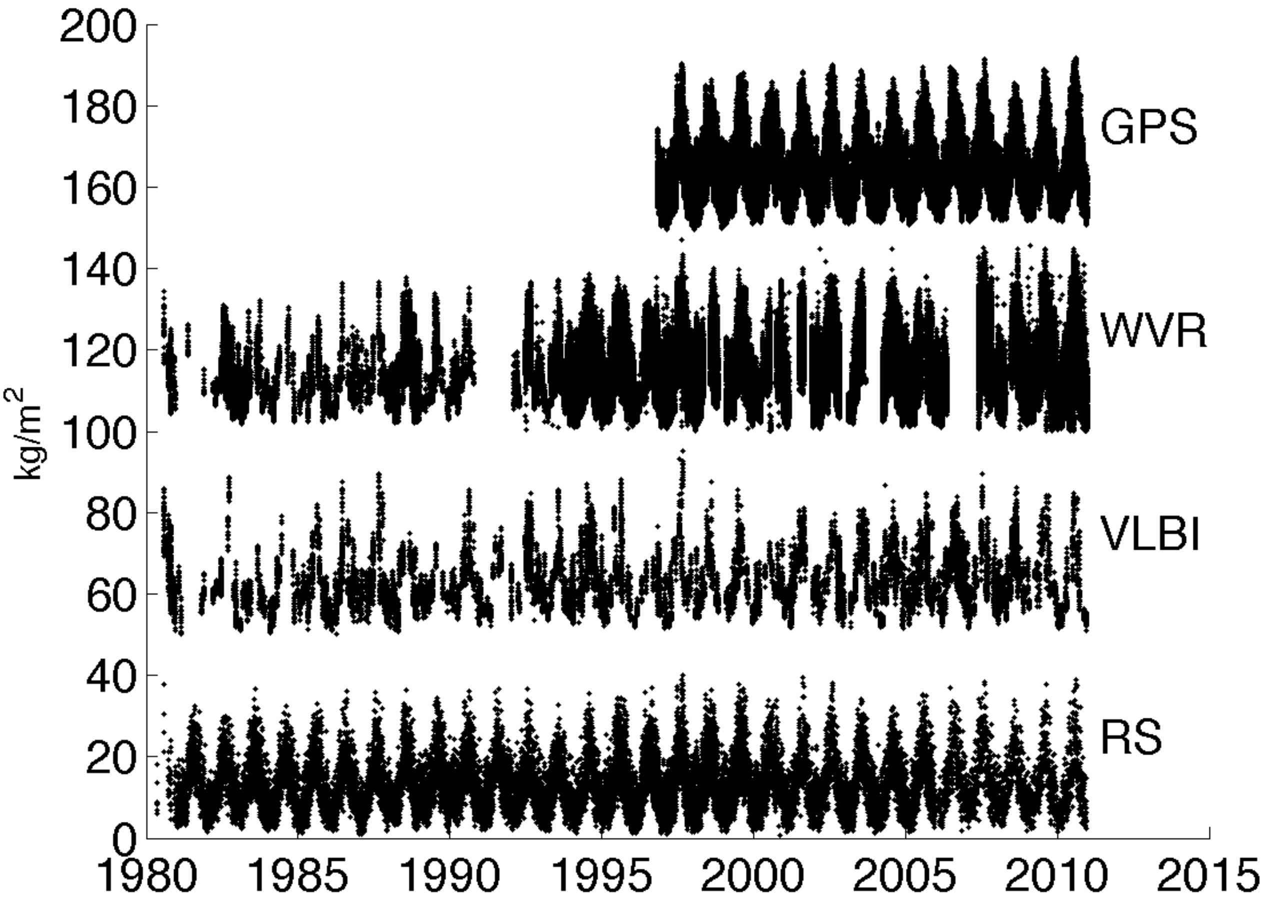

Figure 1. Time series of integrated water vapor (IWV) as determined from radiosondes at Gothenburg-Landvetter airport (RS , bottom), geodetic VLBI data observed at Onsala (VLBI, second from bottom) ground-based microwave radiometry at Onsala (WVR, third from bottom), and GPS at Onsala (GPS, top).

Table 1. Results for linear IPWV trends inferred from geodetic VLBI, microwave radiometer (WVR) and GPS data from Onsala, and radiosonde (RS) data from Gothenburg-Landvetter airport. The uncertainties represent formal errors and are too optimistic by a factor of 5-10.

Data source	Data points	IPWV trend (kg/m^2/decade)
unsynchronized (all) data		
VLBI	15878	0.34 ± 0.03
WVR	378694	0.50 ± 0.01
GPS	120855	0.32 ± 0.02
RS	22368	0.34 ± 0.04

Since the original data have different temporal sampling we also a simple attempt to synchronize the data sets pairwise. The original data sets were reduced to synchronized data sets that include only data points where the time difference between corresponding data points was not longer than the highest temporal resolution of the two datasets to compare.

Examples for scatterplots of the pairwise synchronized data are shown in Fig. 2. The data sets are highly correlated with correlation coefficients above 0.95. It also appears that there are some outliers in some of the data sets.

Again, the seasonal model was fitted to the synchronized data sets and the trend results are shown in Table 2. Table 2 shows mean IWV values, mean IWV differences and the RMS differences for the three synchronization pairs.

The IWV trends for the synchronized data are presented in Table 3. The trends change significantly compared to the individual trends presented in Table 1. This indicates that the synchronization attempt reduces the number of data points considerably and thus makes the analysis more sensitive to weather pattern. The best trend agreement is seen for the VLBI versus WVR comparison where the trends agree within the (too optimistic) formal errors. However, for some of the comparisons the trends of the two techniques compared disagree considerably, which indicates that the chosen synchronization approach is too simple and that there might be outliers in the data sets.

Table 2. Comparison of synchronized IWV data: Mean IWV of the first technique, mean IWV difference, and RMS difference.

Synchronized Comparison	Mean IPWV (kg/m^2)	ΔIPWV (kg/m^2)	RMS (kg/m^2)
VLBI vs. WVR	14.08	0.29 ± 0.01	1.40
VLBI vs. GPS	14.45	0.39 ± 0.01	1.09
VLBI vs. RS	14.01	0.37 ± 0.05	1.82
WVR vs. GPS	13.83	0.40 ± 0.01	1.49
WVR vs. RS	13.84	0.40 ± 0.01	1.57
GPS vs. RS	13.34	0.01 ± 0.01	1.43

Table 3. Comparison of IWV trends from synchronized data sets.

Synchronized Comparison	trend technique-1 (kg/m^2)	trend technique-2 (kg/m^2)
VLBI vs. WVR	0.37 ± 0.02	0.39 ± 0.02
VLBI vs. GPS	0.12 ± 0.07	0.58 ± 0.07
VLBI vs. RS	0.53 ± 0.10	0.47 ± 0.10
WVR vs. GPS	-0.21 ± 0.02	0.05 ± 0.02
WVR vs. RS	0.62 ± 0.04	0.27 ± 0.04
GPS vs. RS	0.19 ± 0.05	0.62 ± 0.06

4. CONCLUSIONS AND OUTLOOK

The presented results show that all four techniques detect individual positive IWV trends on the order of 0.3 to 0.5 kg/m^2 per decade, which corresponds to 2-3 % in IWV per decade. However, the individual trends do not agree and the formal errors presented are much too optimistic and have to be inflated by a factor of 5-10 to represent more realistic uncertainties.

The different temporal resolution and the data gaps are still a problem for the comparison of the data sets. The very simple attempt that was used to to synchronize the data sets has a significant impact on both the number of data points used in the analysis and impacts the derived IWV trends significantly. However, there are only small biases of less than 0.5 kg/m^2 between the synchronized IWV data sets, the RMS-differences are below 2 kg/m^2, and the correlation coefficients are larger than 0.95.

Future work will concentrate on methods to integrate and combine the data sets in order to derive robust estimates of potential IWV trends.

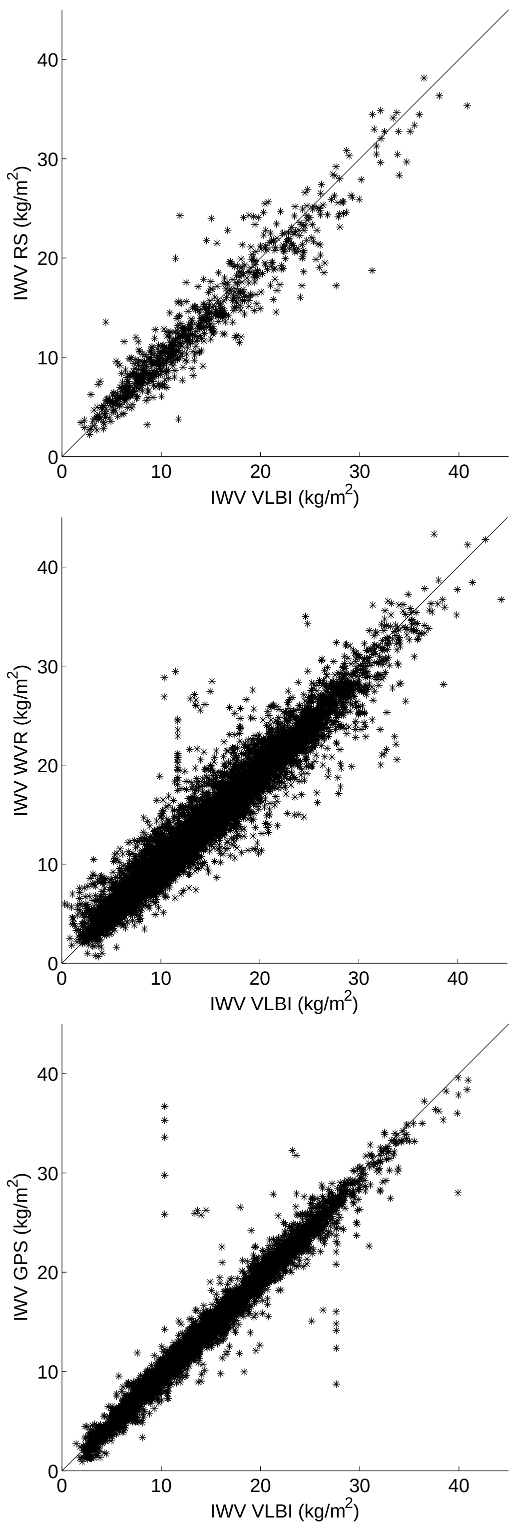

Figure 2. Scatterplots of synchronized IWV data sets: WVR versus VLBI (top), RS versus VLBI (middle), GPS versus VLBI (bottom). The corresponding correlation coefficients are 0.96, 0.98 and 0.95, respectively.

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