MONITORING LONG TERM VARIABILITY IN THE ATMOSPHERIC WATER VAPOUR CONTENT USING GROUND-BASED GPS RECEIVER NETWORKS

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ABSTRACT

We have processed 14 years of observations acquired from 33 GPS sites in Sweden and Finland. Estimated linear trends in the atmospheric Integrated Water Vapour (IWV), using a 10° elevation cutoff angle, are in a range from −0.4 to +0.6 kg/m^2/decade with a typical uncertainty of 0.3–0.4 kg/m^2/decade. The data from 13 GPS sites were processed for 8 different elevation cutoff angles from 5° to 40°. The resulting IWV trends were compared to the trends obtained from the data acquired at seven nearby radiosonde sites. The results show a clear variation in the trend correlation between the two techniques when different elevation cutoff angles are applied to the GPS data analysis. The best agreement is seen for the 25° solution resulting in a correlation coefficient of 0.79.

Key words: atmospheric integrated water vapour; GPS; radiosondes; elevation cutoff angles.

1. INTRODUCTION

The surface temperature of the Earth increases by the absorption of visible radiation from the Sun and decreases by the emission of infrared radiation to space. The existence of greenhouse gases in the atmosphere, such as water vapour, has significant impact on this balance by absorbing and re-emitting the infrared radiation. Hence, water vapour affects the output from models of the Earth's climate system. For example, evaporation and condensation (e.g. [1], [2]) relate to the cycle for water in and on the ground and in the atmosphere, which redistributes energy and affects the precipitation and soil moisture. Therefore, monitoring the long term variation in the atmospheric water vapour gives additional information of the climate variability.

The traditional observational technique for measurements of vertical profiles of pressure, temperature, and water vapour in the atmosphere is the launch of radiosondes (see e.g. [3]). They are, however, affected by a lower accuracy at low temperatures and at very low moisture contents. There may also be systematic errors due to differences in instrument calibration.

Water vapour radiometers (WVR) can measure the integrated amount of water vaour in the atmosphere–often referred to as Integrated Water Vapour (IWV). The WVR can provide almost continuous measurements in any direction on the sky but its retrieval algorithm breaks down during rain [4].

Based on the timing of radio waves propagating through the atmosphere, the ground-based Global Navigation Satellite Systems (GNSS), e.g. the Global Positioning System (GPS), can be used to monitor the IWV [5]. With the advantage of working in principle under all weather conditions, and with an increasing spatial resolution due to growing ground-based GPS networks, GPS has proven to be useful for providing long term measurements of the IWV. Earlier studies (e.g. [6] and [7]) found positive IWV trends in general over Sweden using 9 and 10 years of GPS observations, respectively. These results need to be updated when the GPS time series are getting longer, and when improvements are made in the data processing (i.e. the model for absolute calibration of antenna phase centre variations, as well as new GPS orbit and clock products).

Here, we present linear IWV trends estimated from GPS observations for a 14 year time period over Sweden and Finland. The GPS data processing including the improvements mentioned above, and the model used for the trend estimation, are described in Section 2. Section 3 shows the obtained trends and the sensitivity of the trends to different selected time periods. The elevation cutoff angle, for observations to be included in the GPS data processing, has a significant impact on the estimated IWV trend, which is discussed in Section 4. The paper is ended by the conclusions in Section 5.

2. DATA ANALYSIS

We used GPS observations acquired from 21 Swedish and 12 Finnish sites, from 1 Jan. 1997 to 31 Dec. 2010. We processed the GPS data using the GIPSY/OASIS II [8] and the Precise Point Position (PPP) strategy [9].

The version 5.0 enables the use of the new GPS orbit and clock products provided from a reprocessing of existing archives (`http://gipsy.oasis.jpl.nasa.gov/gipsy/docs/GipsyUsersAGU2007.pdf`). The absolute calibration of Phase Centre Variations (PCV) was implemented in the data processing for all satellite and ground-based antennas [10]. The tropospheric parameters (i.e. the Zenith Wet Delay (ZWD) and the horizontal delay gradients) were estimated along with station coordinates and clock biases using an elevation cutoff angle of 10°, and the Niell Mapping Functions (NMF) [11]. The estimated ZWD has a temporal resolution of 5 min. A model presented in [12] depending on the latitude of the site and the day of the year was used to convert the ZWD to the IWV.

Linear trends in the IWV were estimated using the model [7]:

$$y = y_0 + a_1 t + a_2 \sin(2\pi t) + a_3 \cos(2\pi t) + a_4 \sin(4\pi t) + a_5 \cos(4\pi t) \quad (1)$$

where y and t are the IWV and the time in years (from 1 Jan. 1997 at UTC 0:00 to 31 Dec. 2010 at UTC 24:00), respectively. The unknown coefficients y_0, a_1, a_2, a_3, a_4, and a_5 were determined through the method of least squares. The uncertainty of the IWV trend can be calculated by using the differences between the model fit and the real observations, which are actually correlated up to several days. Nilsson and Elgered [7] presented a method to estimate the uncertainty of the trend taking this short term variability into account, giving a formal 1-σ uncertainty in the IWV trend of 0.4–0.5 kg/m^2/decade for their 10 year time series. For our 14 year long time series, the typical formal uncertainty in the trends decreases to 0.3–0.4 kg/m^2/decade. More details regarding the uncertainty of the trend are discussed in Section 4.

3. IWV TRENDS

Figure 1 depicts the geographical pattern of the obtained linear IWV trends for the 33 GPS sites. In general we have negative trends in the north while there are positive trends in the south. The trends are in the range from −0.4 to +0.6 kg/m^2/decade. These are smaller than those reported by [7] (−0.5 to +1.0 kg/m^2/decade) for a shorter time period (21 Nov. 1996 to 20 Nov. 2006). Also depicted in Figure 1 are the trends for two different selected time periods using the data from the first 13 years (1 Jan. 1997 to 31 Dec. 2009) and from the later 13 years (1 Jan. 1998 to 31 Dec. 2010), respectively. As expected, the sensitivity of the trends to the different time periods seen here is smaller than when using only 8 years of data [7]. However, we can still see some large trend differences for some sites (e.g. SUN0 and KIVE). This indicates that a 13 year period is still too short in order to obtain stable trends. An unusually wet or dry year either in the beginning or in the end of the selected time series will have a significant impact on the estimated IWV trend.

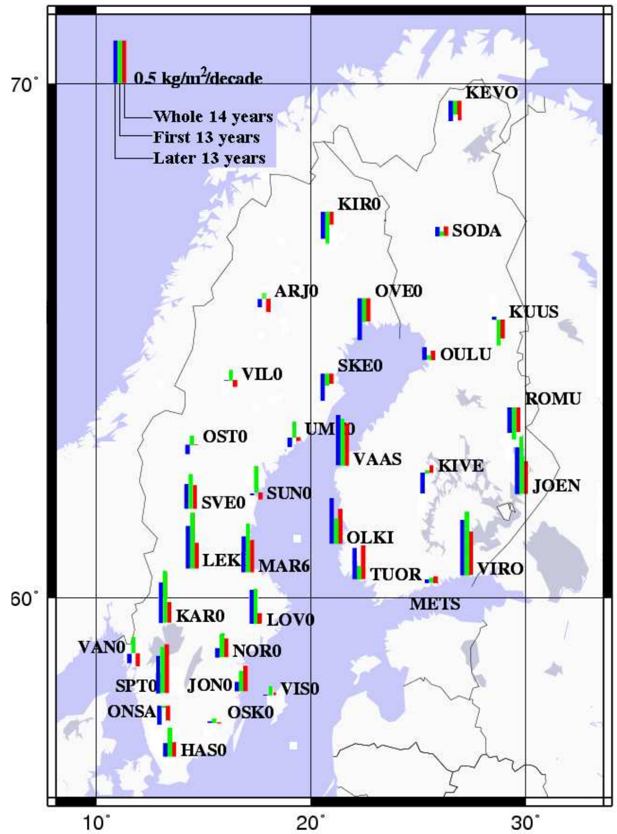

Figure 1. Estimated linear trends in the IWV for 21 Swedish and 12 Finnish sites using the whole 14 year data (red bars), the first 13 years of data (green bars), and the later 13 years of data (blue bars).

We also investigated the difference in IWV trends obtained from different seasons. In Figure 2, it is evident that the summer trends are larger than the trends for the winter. This difference could be due to the sensitivity to different time periods, as discussed above. Therefore, an even longer time period is necessary to reveal if there is a persistent difference in the IWV trends for the different seasons.

4. ELEVATION CUTOFF ANGLES

The uncertainty of the IWV trend is mostly caused by the short term variability of the IWV and not so much due to the formal uncertainties in the IWV estimates [7]. Therefore, using a high elevation cutoff angle for the estimation of IWV trends may be an advantage in order to avoid some systematic errors from observations at lower elevation angles (such as multipath). In order to assess this question, we studied the impact of using different elevation cutoff angles, in a multiple reprocessing of the entire GPS data set.

We selected 13 out of the 33 GPS sites and carried out eight different analyses using elevation cutoff angles

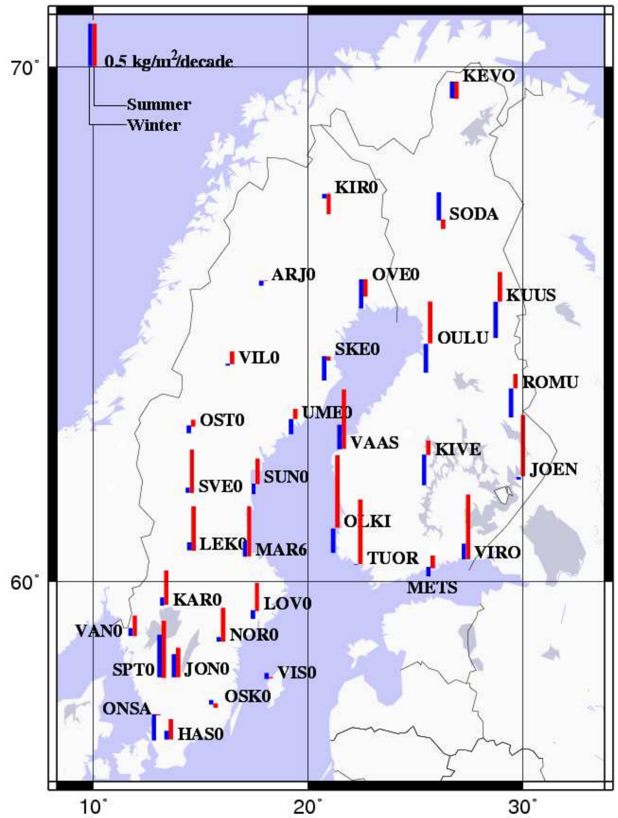

Figure 2. Estimated IWV trends for summer (red bars) and winter seasons (blue bars).

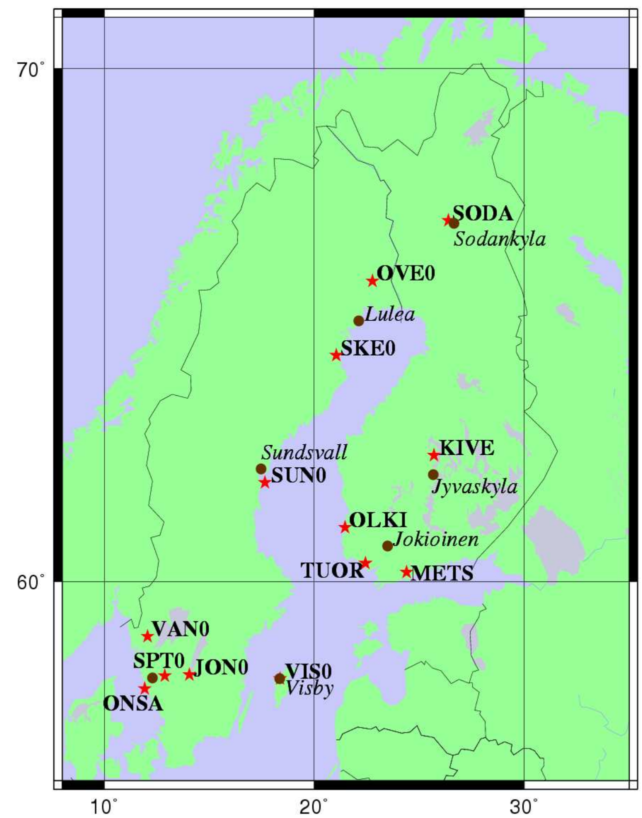

Figure 3. The geographic distribution of the 13 GPS (stars) and the 7 radiosonde (dots) sites (from [13]).

varying from 5° to 40°. The GPS-derived IWV trends were then compared to the trends obtained by the data acquired from seven nearby radiosonde sites (Figure 3). The maximum distance between any pair of compared GPS and the radiosonde sites is 120 km.

Figure 4a depicts the ratio of the number of analyzed observations to the total number of observations for each elevation cutoff angle, which drops below 50% when the angle is higher than 25°. For each solution, the corresponding typical formal uncertainty of the estimated IWV, given by the GIPSY processing, is shown in Figure 4b. As expected, the scatter of the estimated IWV is highly elevation dependent and increases approximately from 0.3 kg/m^2 up to 5 kg/m^2 when the elevation cutoff angle changes from 5° to 40°. If we incorrectly consider the short term variability of the IWV to be independent (white noise), the 1-σ uncertainty of the trend is determined by the formal uncertainty of the estimated IWV and the length of the time period. Figure 4c depicts such trend uncertainties, which are typically less than 0.05 kg/m^2/decade when the elevation cutoff angle is below 30° and increase with the elevation cutoff angle. As discussed in Section 3, deviations from the model, which does not allow for any variation over time scale less than half a year, are actually correlated up to several days. Figure 4d depicts the trend uncertainties after taking this short term correlation into account. The trend uncertainties are now at least a factor of 7 larger than the ones given in Figure 4c when the angle is below 30°. We also note that now the IWV variability determines the uncertainty. This means that the dependence on the elevation cutoff angle is almost completely removed except for KIVE and SODA. This may be explained by the accumulation of snow and ice on the radomes at these sites during winter seasons [14].

Figure 5 plots the radiosonde-derived trends against the GPS-derived trends for 8 different elevation cutoff angles. The correlation varies for different angles. The best agreement (correlation coefficient of 0.79) is seen for the 25° solution. A worse agreement is seen for the 5° solution possibly due to systematic effects. For example, multipath and satellite geometry effects have been shown to cause significant variations in long time series of coordinates [15] and such variations are, therefore, also expected to be seen in time series of the estimated IWV. For elevation cutoff angles larger than 25°, the degraded correlation is assumed to be due to the much larger formal errors of the IWV estimates caused by the fact that too few data points (below 50% of all observations) are included in the data processing.

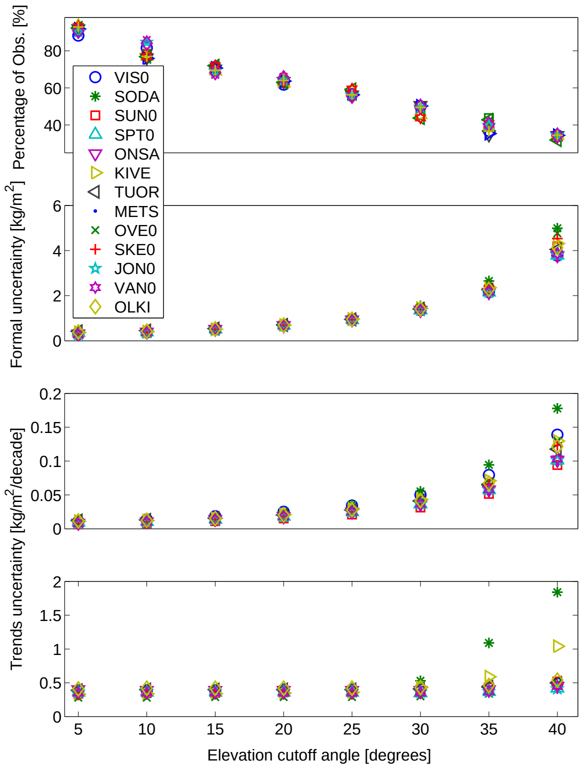

Figure 4. (a) The percentage of observations included in the analysis for each elevation cutoff angle relative to the total observations for a typical 24 h period. (b) The formal uncertainty of the IWV estimates given by the GIPSY processing. The uncertainties of the IWV trends obtained (c) by assuming a white noise behaviour of the IWV short term variation and (d) by taking the short term temporal correlation of the IWV into account (from [13]).

5. CONCLUSIONS

This study updates earlier results of long term trends in the atmospheric IWV using ground-based GPS networks. Fourteen years of observations provide estimates of linear IWV trends for 21 sites in Sweden and 12 sites in Finland. They range from -0.4 to $+0.6$ kg/m^2/decade using a 10° elevation cutoff angle, with a typical uncertainty of 0.3–0.4 kg/m^2/decade. Our trends are smaller than the previously reported results [7]: -0.5 to $+1.0$ kg/m^2/decade with an uncertainty of 0.4–0.5 kg/m^2/decade for a period of ten years. As expected, our results are also less sensitive to the omission of one year of data in the beginning or in the end of the time series.

In order to investigate the impact of using different elevation cutoff angles on the resulting IWV trends, we selected 13 GPS sites and processed the data using 8 different elevation cutoff angles varying from 5° to 40°. Those GPS-derived trends were compared to the trends obtained from seven nearby radiosonde sites. The best

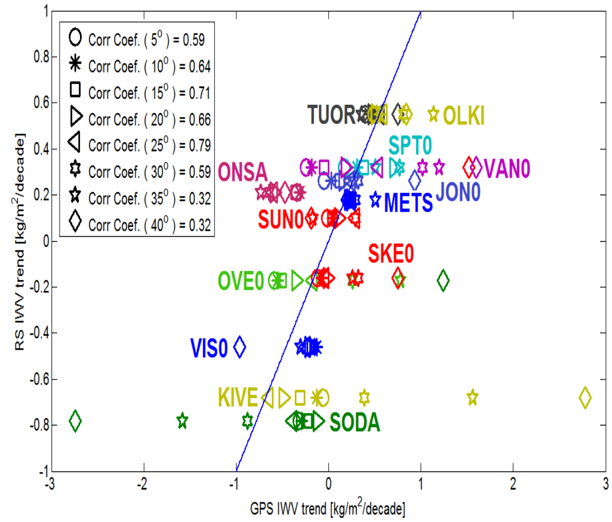

Figure 5. Correlations in the IWV trends between the radiosonde and the GPS data for 8 different elevation cutoff angles. Also shown is the line of perfect agreement (from [13]).

agreement between GPS and radiosonde trends is seen for the 25° solution with a correlation coefficient of 0.79. Several, but not all, of the GPS sites show a significant sensitivity in the estimated trend depending on the elevation cutoff angle. Therefore, we suspect that the effect is caused by signal multipath and intend to investigate that further.

ACKNOWLEDGMENTS

This work was supported by VINNOVA, the Swedish Governmental Agency for Innovation Systems, project P29459-1 “Long Term Water Vapour Measurements Using GPS for Improvement of Climate Modelling”. The maps were produced using the Generic Mapping Tools [16].

REFERENCES

[1] Bengtsson, L. (2010). The global atmospheric water cycle. *Environ. Res. Lett.* 109, doi: 10.1088/17489326/5/025002.

[2] Sherwood, S.C. & Roca, R. & Weckwerth, T.M. & et al. (2010). Tropospheric Water Vapor, Convection, and Climate. *Rev. Geophys.*, 48, RG2001, doi:10.1029/2009RG000301.

[3] Gaffen, D. J. & Sargent, M. A. & Habermann, R. E. & et al. (2000). Sensitivity of tropospheric and stratospheric temperature trends to radiosonde data quality, *J. Climate*, 13, 1776–1796.

[4] Elgered, G. & Jarlemark, P.O.J. (1998). Ground-based microwave radiometry and long-term observa-

tions of atmospheric water vapor. *Radio Sci.* 33, 707-717.

[5] Wang, J. & Zhang, L. (2008). Systematic errors in global radiosonde precipitable water data from comparisons with ground-based GPS measurements. *J. Clim.* 21(10), 2218C2238, doi:10.1175/2007JCLI1944.1.

[6] Gradinarsky, L.P. & Johansson, J.M. & Bouma, H.R. & et al. (2002). Climate monitoring using GPS. *Phys. Chem. Earth*. 27, 335–340, doi:10.101/S1474-7065(02)00009-8.

[7] Nilsson, T. & Elgered, G. (2008). Long-term trends in the atmospheric water vapor content estimated from ground-based GPS data. *J. Geophys. Res.* 113, doi:10.1029/2008JD010110.

[8] Webb, F.H. & Zumberge, J.F. (1993). An Introduction to the GIPSY/OASIS-II. *JPL Publ.* D-11088, Jet Propulsion Laboratory, Pasadena, California.

[9] Zumberge, J.F. & Heflin, M.B. & Jefferson, D.C. & et al. (1997). GPS Trends in Precise Terrestrial, Airborne, and Spaceborn Applications. *J. Geophys. Res.* 102, 5005–5017.

[10] Schmid, R. & Steigenberger, P. & Gendt, G. & et al. (2007). Generation of a consistent absolute phase center correction model for GPS receiver and satellite antennas. *J. Geod.* 81, 781–798, doi:10.1007/s00190-007-0148-y.

[11] Niell, A.E. (1996). Global mapping functions for the atmosphere delay at radio wavelengths, *J. Geophys. Res.*, 101, 3227–3246, doi:10.1029/95JB03048.

[12] Emardson, T.R. & Derks, H.J.P. (2000). On the relation between the wet delay and the integrated precipitable water vapor in the European atmosphere. *Meteorol. Appl.* 7, 61-68, doi:10.1017/S1350482700001377

[13] Ning, T. & Elgered, G. (2011). The impact of the elevation cutoff angle on trends in the atmospheric water vapor content estimated from ground-based GPS. *Geophys. Res. Lett.*, submitted.

[14] Johansson, J.M. & Davis, J.L. & Scherneck, H-G. & et al. (2002). Continuous GPS measurements of postglacial adjustment in Fennoscandia 1. Geodetic results. *J. Geophys. Res.*, 1079(B8), doi:10.1029/2001B000400.

[15] King, M.A. & Watson, C.S. (2010). Long GPS coordinate time series: Multipath and geometry effects. *J. Geophys. Res.*, 115, B04403 doi:10.1029/2009JB006543.

[16] Wessel, P., & Smith, W.H.F. (1998). New, improved version of generic mapping tools released. EOS Trans. *Amer. Geophys. U.* 79(47), 579.