VALIDATION OF CLIMATE MODELS USING EUROPEAN GROUND-BASED GNSS OBSERVATIONS

G. Elgered[1], R. Emardson[2], P. Jarlemark[2], J. Johansson[1], E. Kjellström[3], T. Nilsson[1,4], T. Ning[1], and U. Willén[3]

[1]*Department of Radio and Space Science, Chalmers Univ. of Technol., Onsala Space Observatory, SE-43992 Onsala*
[2]*SP Technical Research Institute of Sweden, SE-50115 Borås*
[3]*Swedish Meteorological and Hydrological Institute, SE-60176 Norrköping*
[4]*Institute of Geodesy and Geophysics, Vienna University of Technology, AT-1040, Vienna*

ABSTRACT

We summarize an ongoing research project where we assess the quality of time series of the Integrated Water Vapour in the atmosphere estimated from ground-based GNSS data for the application of validating and possibly improving climate models. The focus is on the factors limiting the accuracy and especially the long-term stability of the GNSS technique. Higher order ionospheric corrections have been studied, using realistic values for the Total Electron Content (TEC) close to the solar maximum in 2002. Averaged over ten days we find that the impact in the mean IWV is less than 0.1 kg/m^2. Another factor is the model used for antenna phase centre variations. We have studied this effect on the IWV estimates by simulations and by studying estimates of the IWV based on observed GPS signals. We find that ignoring satellite antenna phase variations, when processing GPS data from 2003–2008, can significantly influence the values of the estimated linear trends. The value depends on the latitude of the site as well as on the elevation cut-off angle used in the data analysis. Finally, we show a significant correlation between estimated linear trends in the IWV and the corresponding linear trends in the independently observed ground temperature.

Key words: GNSS; GPS; atmospheric water vapour, climate model validation.

1. INTRODUCTION

Water vapour is an important green-house gas [1]. Accurate measurements of water vapour in the atmosphere are in general difficult and costly to carry out with high temporal and spatial resolution over long time. Ground-based GNSS receiver networks provide measurements of differences in time of arrival. When these observations are acquired at different elevation angles it is possible to estimate an equivalent zenith propagation delay due to water vapour [2], which in turn can be used to derive the atmospheric content of Integrated Water Vapour (IWV).

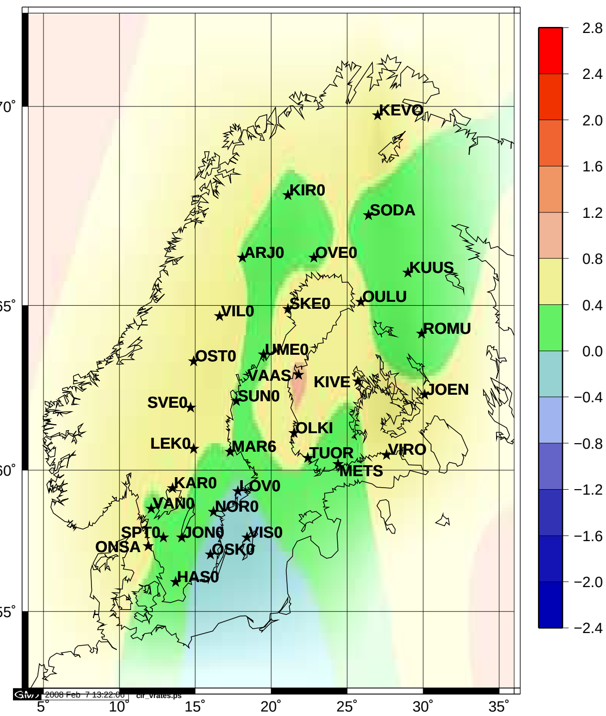

Figure 1. Estimated linear trends in the IWV from 1996 to 2006 (from [3]). The unit for the IWV trend is kg/m^2/decade.

Since time is a physical parameter, which we can measure with high accuracy, also over long time periods, it is a promising method for providing an observational system for climate monitoring. As continuously operating GNSS receivers are increasing in numbers the spatial resolution will continue to improve. Many countries today have networks with typical baseline lengths from 100 to 200 km.

In an earlier study *Nilsson and Elgered* [3] used ten years of ground-based data from the Global Positioning System (GPS) acquired at 33 GPS receiver sites in Finland and Sweden. Although ten years is much too short to search for climate change here we assess the stability and consis-

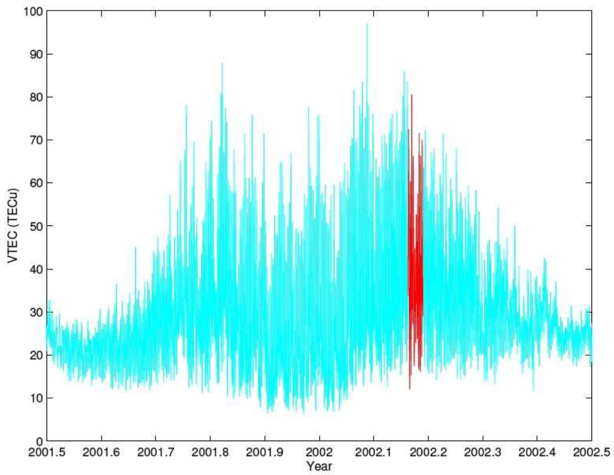

Figure 2. Vertical TEC for the site Onsala during one year. The study period in this report is marked in red.

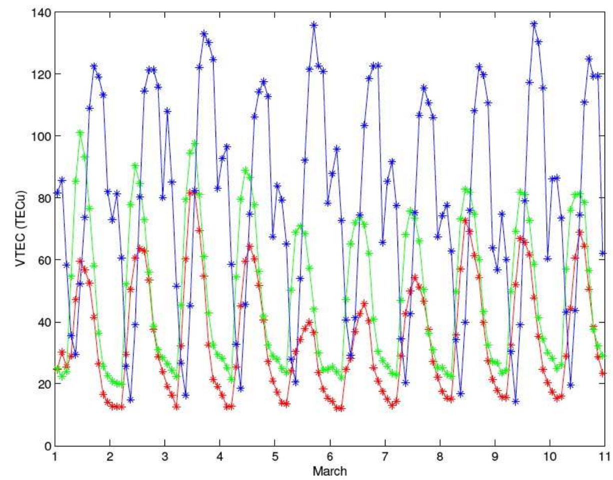

Figure 3. Vertical TEC for the sites Onsala (red), Matera (green), and Kourou (blue) 10 days in March 2002.

tency of the linear trends of the water vapour content that were estimated from that data set. The linear trends in the water vapour content are shown in Figure 1 and range from -0.5 to +1.0 kg/m^2/decade. The formal uncertainty of these trends—taking the temporal correlation of the variability about the estimated model into account—is of the order of 0.4 kg/m^2/decade. This means that we require approximately 30 years of data in order to clearly detect trends of about 0.1 kg/m^2/decade—an interesting coincidence since also the standard averaging period of meteorological parameters in climate studies is 30 years [4].

This uncertainty is entirely estimated based on statistical theories. In this presentation we assess other types of errors which show a more systematic behaviour. In Section 2 we present a study of the possible influence of higher order ionospheric effects on the propagation delay. Section 3 deals with the influence caused by variations of satellite and antenna phase centres. An alternative method to address the quality of the estimated trends in the IWV is to compare them with other independently observed meteorological parameters. In Section 4, such an analysis is made between the IWV and the ground temperature trends estimated at 20 of the Swedish sites in Figure 1. Finally, in Section 5 we present the conclusions and discuss possible future work.

2. IONOSPHERIC EFFECTS

The main component of the ionospheric propagation delay for GPS signals has a frequency dependency proportional to $1/f^2$. The traditional "ionosphere-free" linear combination of the GPS observables at the two frequencies aims to cancel this component. However, a smaller contribution from the ionosphere to the signal delay remains. In presence of the Earth's magnetic field $\vec{B}$ the free electrons in the ionosphere will give rise to a Faraday rotation of the GPS signals. An apparent propagation delay, d_F is written

$$d_F = C_F \cdot \vec{B} \cdot \vec{k} \cdot I \cdot \frac{1}{f^3} \qquad (1)$$

where C_F is a constant value; $\vec{k}$ is the direction of the signal propagation; I is the total amount of free electrons along the propagation path, the Total Electron Content (TEC); and f is the frequency of the GPS signal. *Kedar et al.* [5] have presented a detailed discussion on this effect, including its impact on GPS coordinate estimation using a time series of three years.

We used data acquired during 10 days in March 2002—a period close to the peak in TEC values during the approximately eleven year long solar cycle—from the sites Onsala (latitude 57°N), Matera (latitude 41°N), and Kourou (latitude 5°N) in the tracking network of the International GNSS Service (IGS) [6]. TEC maps were obtained from the Jet Propulsion Laboratory in order to determine the local TEC values at the three sites, see Figures 2 and 3. The magnetic field was obtained from the model presented by *Kedar et al.* [5]. It is an ideal dipole through the centre of the Earth and with its south pole at the latitude 78.5°N and the longitude 103.0°W. The field strength is calculated for a height of 400 km above the Earth's surface, where the whole Faraday rotation effect is assumed to occur.

We processed the GPS observables using the GIPSY software package [7]. We also created a second data set based on the same observables and compensated for the higher order ionospheric effect using Equation 1. This data set was processed in an identical way as the processing of the original data set. Finally, the atmospheric delay estimates from the processing of the two data sets were compared.

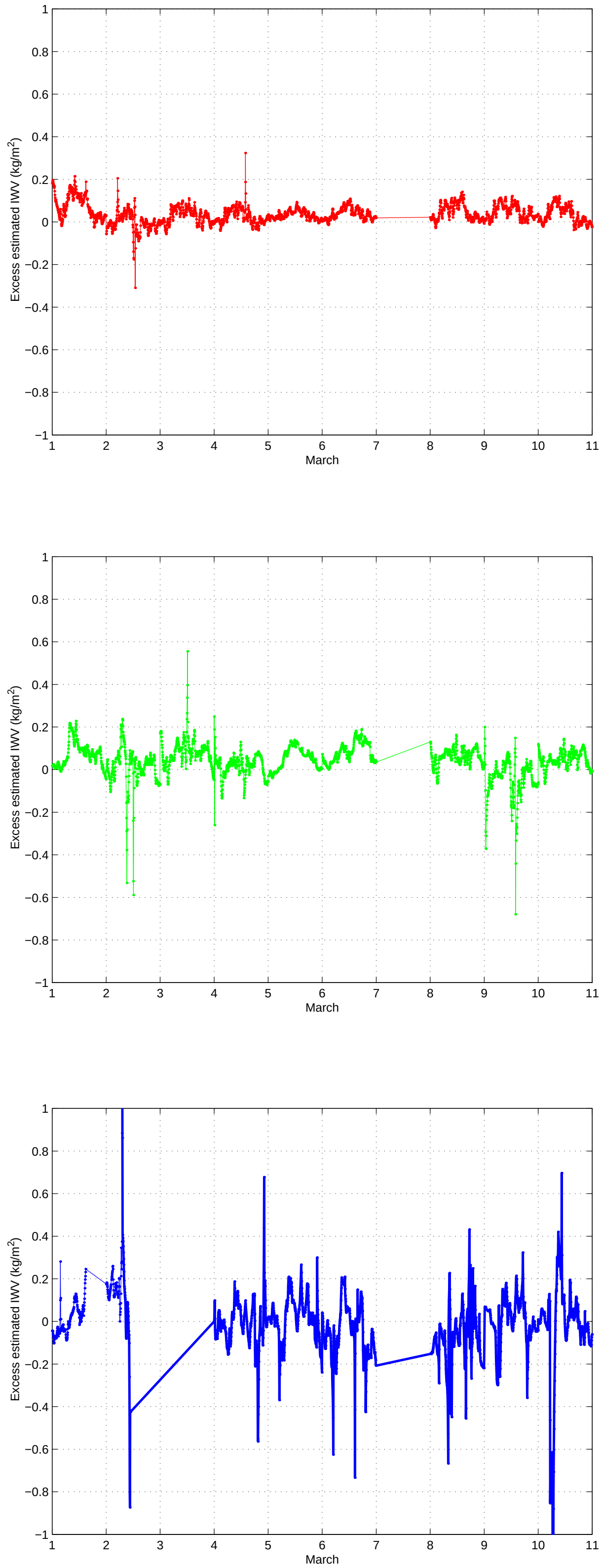

Figure 4. Differences between the IWV estimates with and without compensation for the Faraday rotation effect for Onsala (top), Matera (middle), and Kourou (bottom).

The resulting differences between the atmospheric delay estimates with and without compensation for the Faraday rotation effect were converted to IWV and presented in Figure 4. The mean IWV differences and the corresponding mean TEC values for the three sites are summarized in Table 1.

Table 1. Mean IWV differences

Site	Latitude ($^\circ$N)	Mean TEC (TECU)^a	Mean IWV Diff. (kg/m^2)
Onsala	57	35.4	0.03
Matera	41	49.2	0.04
Kourou	5	79.5	0.00

^{a} TECU = 1 TEC unit = 10^{16} electrons/m^2

At the two most northern sites the omission of the higher order ionospheric effect results in a systematic error in the estimated IWV. The effect is, however, small. Closer to the equator this effect is in general larger, due to the higher TEC values. However, no systematic offset is observed for this site. This can be explained by the direction of the magnetic field as observations at a certain elevation angle from south are compensated by observation from north. Closer to the north pole all observations result in positive offsets in the IWV.

We find that presumably unmodelled ionospheric higher order effects are not a significant error contribution to IWV trend estimates over time scales of ten years or longer. These effects may, however, be significant in other meteorological applications.

We have in this study only investigated the direct influence of unmodelled ionospheric higher order effects in IWV estimates for ground based receivers. The effects on satellite orbit estimation and the following indirect consequences for IVW estimates remains a subject for further studies.

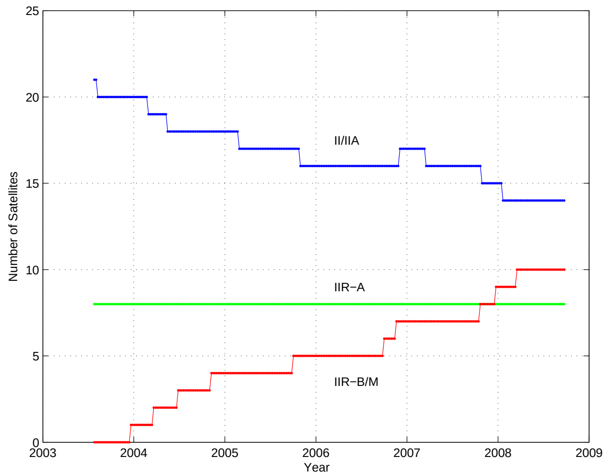

Figure 5. Number of satellites of type II/IIA (blue), IIR-A (green), and IIR-B/M (red) during 2003 to 2008 (from [9]).

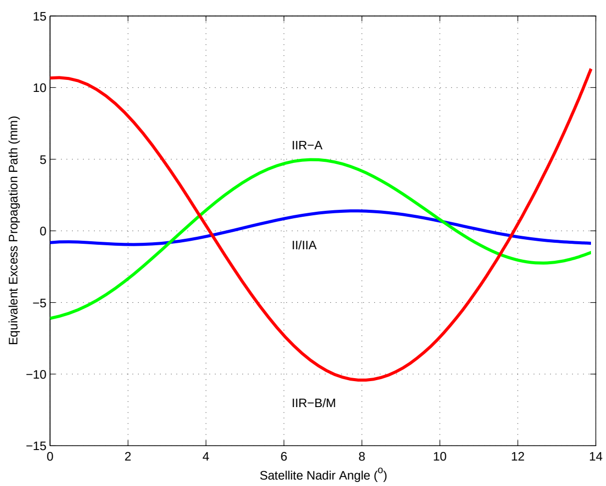

Figure 6. Antenna phase center variations vs. the nadir angle from the satellite to the ground receiver or the three satellite types II/IIA (blue), IIR-A (green), and IIRB/M (red) (from [9]).

3. ANTENNA PHASE CENTRE EFFECTS

During a period of five years, from 2003 to 2008, a new GPS satellite type was introduced and steadily grew in numbers (see Figure 5). The antenna phase centre variations (PCVs) for these satellites deviate from the earlier satellite types (see Figure 6). This model is illustrated in Figure 7; where it is expressed as a function of the elevation angle of the satellite seen from a receiver on the ground. *Schmid and Rothacher* [8] have shown that PCVs have a significant influence on the estimated delay in the neutral atmosphere, and hence also on the IWV.

Processing GPS data from the Onsala site, with and without this model, we have studied the impact of the PCV

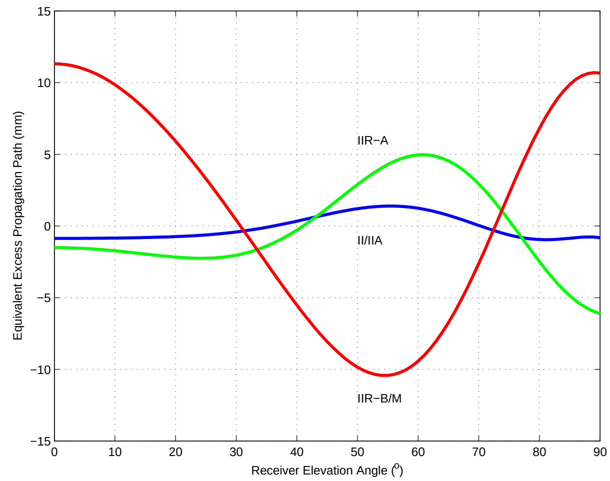

Figure 7. Antenna phase center variations vs. the elevation angle of the satellite seen from the ground receiver for the three satellite types II/IIA (blue), IIR-A (green), and IIRB/M (red) (from [9]).

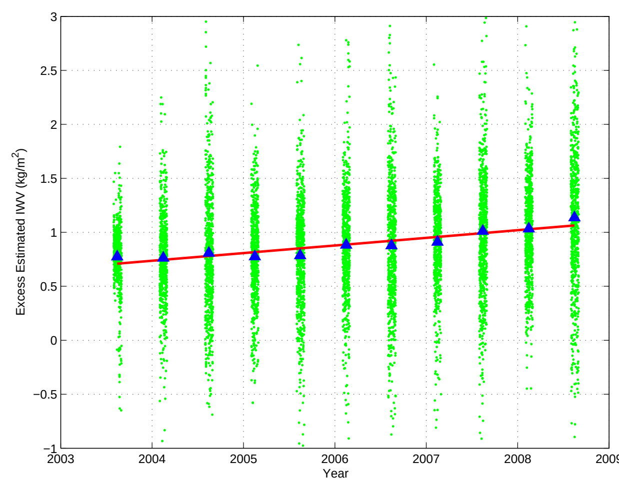

Figure 8. Difference in estimated IWV between two GPS solutions: with and without the antenna (both the satellites and the receiver) phase centre corrections applied. The blue triangles illustrate the mean values for each month. The red line in the figure is the least squares fit to the estimated IWV differences and has a slope of 0.7 kg/m^2/decade (from [9]).

model on the estimated IWV. Figure 8 shows the difference in the estimated IWV between these two solutions using an elevation cutoff angle of 10°. Additional studies — not shown or further discussed here — have shown that the estimated trend depends on the latitude of the site, as well as on the elevation cutoff angle used in the data processing. See *Jarlemark et al.* [9] for more details on this effect, including its consequences on GPS coordinate estimation.

Table 2. GPS sites and the corresponding observation sites of the ground temperature.

GPS Site Acronym	Name	Longitude [°E]	Latitude [°N]	Height[a] [m]	Met. site Name	Longitude [°E]	Latitude [°N]	Height[a] [m]
KIR0	Kiruna	21.060	67.877	469	Kiruna	20.33	67.82	447
ARJ0	Arjeplog	18.125	66.318	459	Arjeplog	17.84	66.05	431
SKE0	Skellefteå	21.050	64.880	59	Luleå	22.13	65.55	17
VIL0	Vilhelmina	16.559	64.697	420	Gunnarn	17.70	65.00	277
UME0	Umeå	19.509	63.578	32	Umeå	20.28	63.80	8
OST0	Östersund	14.858	63.442	459	Frösön	14.50	63.20	359
SUN0	Sundsvall	17.659	62.232	7	Sundsvall	17.30	62.39	6
SVE0	Sveg	14.700	62.017	458	Sveg	14.18	62.02	363
LEK0	Leksand	14.877	60.722	448	Mora	14.51	60.96	196
MAR6	Mårtsbo	17.258	60.595	51	Gävle	17.16	60.42	16
KAR0	Karlstad	13.505	59.444	83	Karlstad	13.33	59.45	100
LOV0	Lovö	17.830	59.340	56	Stockholm	18.06	59.34	44
VAN0	Vänersborg	12.070	58.690	135	Såtenäs	12.72	58.43	54
NOR0	Norrköping	16.250	58.590	13	Norrköping	16.15	58.58	34
JON0	Jönköping	14.059	57.745	227	Jönköping	14.08	57.75	224
SPT0	Borås	12.891	57.715	185	Borås	12.95	57.76	135
VIS0	Visby	18.367	57.653	55	Visby	18.35	57.67	47
ONSA	Onsala	11.925	57.395	9	Nidingen	11.90	57.30	24
OSK0	Oskarshamn	16.000	57.060	120	Målilla	15.80	57.38	95
HAS0	Hässleholm	13.718	56.092	79	Osby	14.00	56.37	82

[a]The heights are referenced to the mean sea level.

4. IWV AND GROUND TEMPERATURE CORRELATION

A different method to assess the quality of the estimated IWV trends in Figure 1 is to compare them to another independently observed meteorological parameter. Given the relation between the temperature and the saturation pressure of water vapour we expect an increase in the IWV for an increase in the temperature. Following the Clausius-Clapeyron relation, assuming a conservation of the relative humidity, the linear relation between a change in the IWV and a change in the temperature is approximately 6 %/K [10].

We analysed monthly means of ground temperatures from 20 sites in the observational network of the Swedish Meteorological and Hydrological Institute (SMHI) from the same ten year period (November 17, 1996 – November 16, 2006) as we have GPS derived IWV results (see Figure 1). The selected sites are located nearby a GPS station. The locations of the GPS receiver sites and the ground temperature observation sites are shown in Table 2.

Linear trends were estimated also from the ground temperature data using the same model as was used when estimating the IWV trends [3]. A correlation plot between the trends is shown in Figure 9. The correlation coefficient of the data is 0.69, meaning that it has been shown that the two trends are correlated with a probability larger than 99%. It is also interesting to note that the linear slope is 3.8%/K. This indicates either that the relative humidity in this area has not been conserved during the studied time period or that the trends in the ground temperature are not fully representative for the mean temperature of the water vapour in the atmsophere. Additional studies using this as well as different data sets are necessary in order to assess the uncertainty of this parameter.

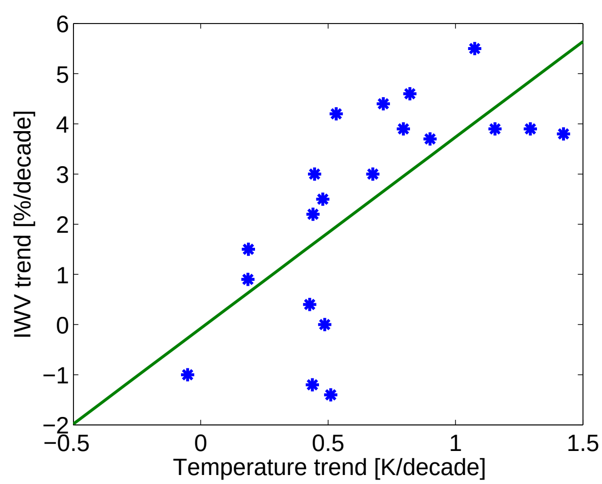

Figure 9. The relation of the estimated IWV trends from the GPS sites in the Swedish GPS network vs. the corresponding estimated trends in the ground temperature at nearby sites. The estimated linear relation (green line) has a slope of 3.8%/K.

5. CONCLUSIONS AND FUTURE WORK

We have assessed the quality of previously estimated trends in the IWV. We find that higher order ionospheric effects seem to be too small to influence the estimated trends, especially if these are based on time series of many years of data. It was also shown that models of phase centre variations of the satellite antennas need to be used, especially over time periods when the relative numbers of different satellite antenna types are varying.

A significant correlation was found between trends in the IWV and trends in the ground temperature for 20 Swedish GPS sites. These IWV trends were derived from a GPS analysis which did not include the satellite antenna model. It is therefore important both repeat this kind of study with the latest GPS processing software as well as to include more sites from other areas.

We are now analyzing GPS data from receiving sites spread over Europe, using the GIPSY/OASIS II analysis software version 5.0 with the latest internationally agreed antenna phase centre models both for the satellite and the ground antennas. Solutions are made with several different elevation cutoff angles and comparisons will be carried out using different climate models in use at the Rossby Centre, the climate modelling research unit at the Swedish Meteorological and Hydrological Institute.

ACKNOWLEDGMENTS

This paper presents a summary and overview of the ongoing (2007–2011) research project “Long Term Water Vapour Measurements Using GPS for Improvement of Climate Modelling” funded by the Swedish Governmental Agency for Innovation Systems (VINNOVA).

REFERENCES

[1] IPCC (2007), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK and New York, NY, USA.

[2] Bevis, M., S. Businger, T.A. Herring, C. Rocken, R.A. Anthes, R.H. Ware (1992), GPS meteorology: remote sensing of atmospheric water vapor using the Global Positioning System, *J. Geophys. Res.*, 97, 15,787–15,801.

[3] Nilsson, T. and G. Elgered (2008), Long-term trends in the atmospheric water vapor content estimated from ground-based GPS data, *J. Geophys. Res.*, 113, D19101, doi:10.1029/2008JD010110.

[4] Førland, E.J., I. Hanssen-Baur, and P.Ø. Nordli (1992), New Norwegian climate normals — but has the climate really changed?, *Norsk Geografisk Tidskrift*, 46, 83–94.

[5] Kedar S. G. A. Hajj, B. D. Wilson, and M. B. Heflin (2003), The effects of the second order GPS ionospheric correction on receiver positions, *Geophys. Res. Lett.*, doi: 10.1029/2003GL017639.

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

[7] Webb F.H., and Zumberge J.F., 1993, An introduction to the GIPSY/OASIS-II, *JPL Publ.*.

[8] Schmid, R., M. Rothacher (2003), Estimation of elevation-dependent satellite antenna phase center variations of GPS satellites, *J. Geodesy*, 77: 440446, doi: 10.1007/s00190-003-0339-0

[9] Jarlemark, P., R. Emardson, J. Johansson, and G. Elgered (2009), Ground-Based GPS for Validation of Climate Models: the Impact of Satellite Antenna Phase Center Variations *IEEE Geosci. Rem. Sens.*, submitted.

[10] Trenberth K.E., A. Dai, R.M. Rasmussen & D.B. Parsons, 2003, The changing character of precipitation, Bull Amer Meteor Soc, 84 (9), 1205–1217, doi:10.1175/BAMS-84-9-1205