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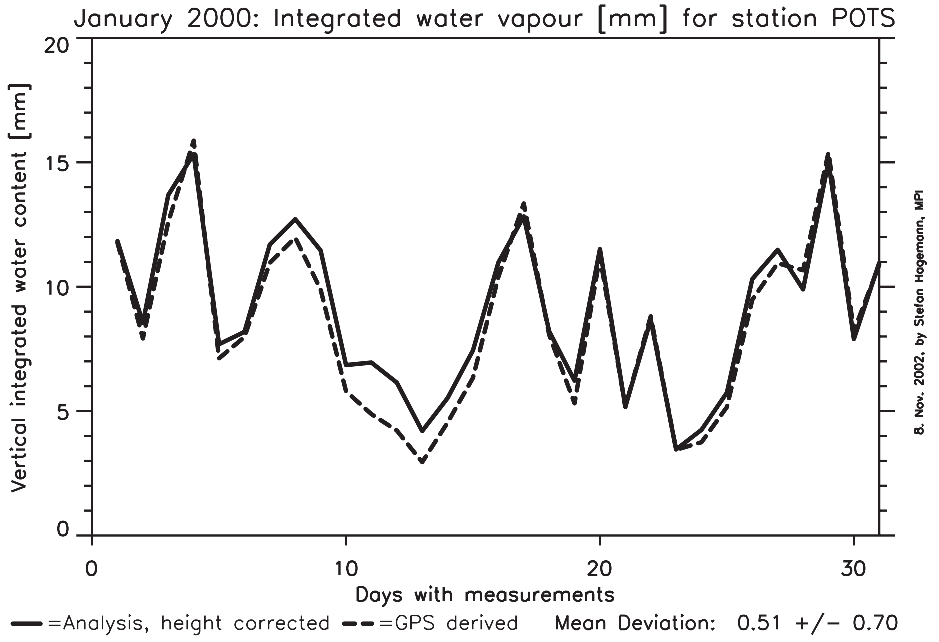

On the determination of atmospheric water vapour from GPS measurements

by

Stefan Hagemann · Lennart Bengtsson · Gerd Gendt

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Authors

Stefan Hagemann	Max-Planck-Institut für Meteorologie Hamburg, Germany
Lennart Bengtsson	Max-Planck-Institut für Meteorologie Hamburg, Germany & Environmental Systems Science Centre Harry Pitt Building, Whiteknights Reading, UK
Gerd Gendt	GeoForschungsZentrum Aufgabenbereich 1 Potsdam, Germany

Max-Planck-Institut für Meteorologie
Bundesstrasse 55
D - 20146 Hamburg
Germany

Tel.: +49-(0)40-4 11 73-0
Fax: +49-(0)40-4 11 73-298
e-mail: <name>@dkrz.de
Web: www.mpimet.mpg.de

On the determination of atmospheric water vapour from GPS measurements

STEFAN HAGEMANN*[1], LENNART BENGTSSON[1, 2] AND GERD GENDT[3]

[1]Max Planck Institute for Meteorology
Bundesstraße 55
D-20146 Hamburg, Germany

[2]Environmental Systems Science Centre
Harry Pitt Building, Whiteknights
PO Box 238, Reading RG6 6AL, UK

[3]GeoForschungsZentrum
Aufgabenbereich 1
Telegrafenberg A17
D-14473 Potsdam, Germany

*e-mail: Hagemann@dkrz.de
http://www.mpimet.mpg.de/~hagemann.stefan
Tel.: +49-40-41173-101
Fax: +49-40-41173-366

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Contents

Abstract

Surface based GPS-based measurements of zenith path delay (ZPD) can be used to derive vertically integrated water vapour (IWV) of the atmosphere. ZPD data are collected in a global network presently consisting of 260 stations as part of the International GPS Service. In the present study ZPD data from this network are converted into IWV using observed surface pressure and mean atmospheric column temperature obtained from the ECMWF operational analyses. For the four months of January/July 2000/2001, the GPS derived IWV values are compared to the IWV from the ECMWF operational analyses with a special focus on the monthly averaged difference (bias) and the standard deviation of daily differences. This comparison shows that the GPS derived IWV values are well suited for the validation of operational analyses of IWV. For most GPS stations, the IWV data agree quite well with the analysed data indicating that they are both correct at these locations. Larger differences for individual days are interpreted as errors in the analyses. A dry bias in the winter is found over central USA, Canada and central Siberia suggesting a systematic analysis error. Larger differences were mainly found in mountain areas. These were related to representation problems and interpolation difficulties between model height and station height.

In addition, the IWV comparison can be used to identify errors or problems in the observations of ZPD. This includes errors in the data itself, e.g. erroneous outlier in the measured time series, as well as systematic errors that affect all IWV values at a specific station. Such stations were excluded from the intercomparison. Finally long term requirements for a GPS-based water vapour monitoring system are discussed.

1. Introduction

Reliable humidity data are crucial for climate monitoring and prediction. Atmospheric water vapour is the dominating greenhouse gas, and so quantifying the feedback of water vapour in global warming is therefore of paramount importance. Indeed, numerical experiments suggest that this effect is substantial. As the climate is warming due to increasing carbon dioxide and other anthropogenic greenhouse gases water vapour is expected to increase rapidly as models broadly conserve relative humidity (*Semenov and Bengtsson*, 2002; *Schneider et al.*, 1999). This will have major consequences for the heat balance of the Earth. For example, *Hall and Manabe* (1999) have found that excluding the effect of water vapour in the long wave radiation calculations of the GFDL model in CO2 doubling experiments reduces the global averaged warming from 3.38K to 1.05K, meaning a water vapour enhancement factor of 3.2. This is significantly larger than the direct effect of water vapour based on energy balance estimates (e.g. *Held and Soden*, 2000), indicating that water vapour feedback is also crucial for other feedback processes, such as snow-sea ice and clouds, that also play a significant role.

Water vapour varies considerably in time and space and the present observing systems are inadequate to monitor water vapour properly (*Gaffen et al.*, 2000). Satellite observing systems using passive radiometry provide a high horizontal sampling but suffer from observational bias, thereby making such data less suitable for monitoring purposes (*Trenberth et al.*, 2001).

Surface based GPS-based measurements offer here new and promising possibilities (*Yuan et al.*, 1993). One of these is the capability to provide data at similar quality under all weather conditions. Regional networks, providing temporally high resolved information of the integrated atmospheric water vapour are being established all around the world; vertical profiling by satellite occultation techniques is similarly taking place.

With the surface based technique, dual-frequency signals are collected at ground-based receivers and used to obtain the signal delay and thus the integrated water vapour along the path from the GPS satellites to the receiver (*Rocken et al.*, 1993, 1995; *Bevis et al.*, 1994; *Businger et al.*, 1996). It is interesting to note that this possibility occurred whilst exploring the cause of errors in geodetic measurements (*Davis et al.*, 1985; *Elgered*, 1993).

There is substantial activity involving ground-based GPS measurements in studies at various scales from national to global. Many of these initiatives are being carried out by research institutions in collaboration with national agencies, principally to assess the accuracy of ground-based GPS estimates of integrated water vapour (IWV) and their utility in improving near-real time weather prediction. But their aim is also to develop and refine the fundamental techniques involved in making the observations, processing the data and making them available in a timely manner. *Bengtsson et al.* (2002a) give an overview of these ongoing activities.

As part of International GPS Service (IGS) a number of countries are collaborating to collect, process and disseminate data from GPS receivers worldwide. Since 1997, a tropospheric product has been compiled using a global network presently consisting of 260 stations (Figure 1). This product is the zenith path delay (ZPD) of the neutral atmosphere, with a sampling rate of two hours and is available with a delay of four weeks. The product is generated from submissions from all the IGS Analysis Centres and therefore has good reliability and an internal consistency of the order of 3 mm ZPD for bias and standard deviation. For about 40 sites the surface meteorological data are also collected and can be directly used for conversion into IWV.

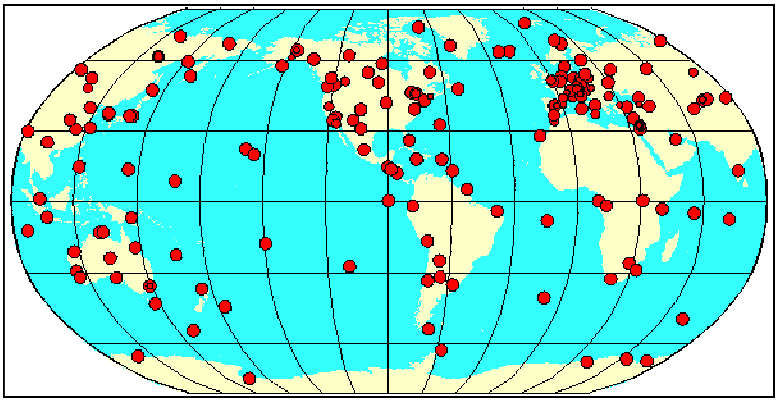

Fig. 1: The IGS network of ground-based GPS stations.

Recently, IGS has started a pilot project to generate a ZPD product with low latency. Presently, it is generated every three hours with a delay of two hours. The product is intended for use by regional groups for checking their near real-time tropospheric products. If needed, the product can be generated much faster, and could even be used for assimilation into global models.

The purpose of this study is to retrieve IWV calculated from the IGS stations and to assess its quality by comparing it with the IWV from the ECMWF operational analyses. The GPS results are taken from the IGS combined tropospheric products, where the estimates of seven centres are combined to get the final ZPD results (*Gendt*, 1999). The ZPD values are converted into IWV using observed surface pressure and mean atmospheric column temperature obtained from the ECMWF operational analyses.

The following science questions are addressed:

- How well does the ECMWF operational forecasting system analyse IWV as compared to those retrieved from GPS measurements?
- To what extent is it possible to separate errors in model analysed IWV from IWV obtained from GPS measurements? What are the most likely sources of errors?
- What are the long term requirements for a GPS-based water vapour monitoring system?

The technical methods how IWV can be derived from the ZPD measurements and how gridded model values can be compared to these point measurements are described in section 2. Section 3 presents the two major applications of the GPS derived IWV values which can be currently made operable. These comprise the identification of errors in the observations and the validation of simulated IWV values which are taken from the ECMWF operational analyses. At the end conclusions and a short outlook on future works are presented in section 4.

2. Computation of integrated water vapour at the GPS station locations

Section 2.1 describes the calculation of the integrated water vapour content IWV from the GPS estimates of zenith path delay. Section 2.2 deals with the methods of interpolating the gridded operational analysis (OA) IWV values to the location and height of the GPS stations. As the surface pressure is crucial for the accuracy of the GPS derived IWV, it is considered in more detail in section 2.3. The general uncertainty of GPS derived IWV is considered in section 2.4.

2.1. Calculation of IWV from ZPD

The GPS signal delay in the atmosphere can be expressed as a zenith path delay (*ZPD)*. According to *Bevis et al.* (1992), the zenith path delay *ZPD* comprises a zenith hydrostatic delay (*ZHD*) and a zenith wet delay (*ZWD*) where the latter is linked to IWV (see Eq. (4)). Thus,

$$ZPD = ZHD + ZWD \tag{1}$$

Following *Yuan et al.* (1993), the zenith hydrostatic delay can be written as a function of the surface pressure P_s in hPa (In Eq. (2), a typing error included in the paper of *Yuan et al.* (1993) is corrected. The correct value is 2.279.):

$$ZHD = (2.279 \pm 0.0024) \cdot \frac{P_s}{f(\lambda, h)} \approx (2.279 \pm 0.0024) \cdot P_s \tag{2}$$

f(λ, h) is a factor close to unity that accounts for the variation in gravitational acceleration with latitude λ and height *h* in km (*Saastamoinen*, 1972):

$$f(\lambda, h) = 1 - 0.00266 \cdot \cos\left(2 \cdot \lambda \cdot \frac{\pi}{180}\right) - 2.8 \cdot 10^{-4} \cdot h \tag{3}$$

The zenith wet delay depends upon the vertical distribution of water vapour and can be directly related to *IWV* by Eq. (4).

$$IWV \cdot \rho_{H2O} = \kappa \cdot ZWD \tag{4}$$

with a proportional coefficient κ yielded from

$$\frac{1}{\kappa} = 10^{-6} \cdot \left(\frac{c_1}{T_m} + c_2\right) \cdot R_V \tag{5}$$

where

$$c_1 = (3.776 \pm 0.03) \cdot 10^5 \frac{\mathrm{K}^2}{\mathrm{hPa}}$$

and

$$c_2 = (17 \pm 10) \frac{\mathrm{K}}{\mathrm{hPa}}$$

Here, R_v is the specific gas constant for water vapour (461.45 J/kg/K) and ρ_{H2O} is the density of water (1000 kg/m^3). T_m is the vertically integrated mean temperature within an atmospheric column represented by N levels, and it is given by

$$T_m = \frac{\int \frac{P_v}{T} dz}{\int \frac{P_v}{T^2} dz} \approx \frac{\sum_{i=1}^{N} \frac{P_i}{T_i}}{\sum_{i=1}^{N} \frac{P_i}{T_i^2}} \qquad (6)$$

As suggested by *Bevis et al.* (1992, 1994) T_m can suitably be determined from operational weather prediction models. Here we have used the ECMWF operational analyses (OA) to estimate T_m. The accuracy of GPS derived IWV values is comparatively robust against uncertainties in T_m. Thus, the use of OA values seems to be appropriate. For the amounts of uncertainty in *IWV* induced by variations in *ZPD*, P_s, and T_m, see section 2.4.

The ECMWF model has 60 vertical levels starting near the surface and reaching up into the upper stratosphere at about 60 km height so that Eq. (6) becomes a fraction of two discrete sums over these levels. The current spectral resolution is T511 which corresponds to a spatial resolution of about 40 km in mid-latitudes. Since we later intend to use the 40 years re-analyses (ERA40) currently produced at ECMWF at a coarser resolution of about 110 km, the OA data are interpolated accordingly.

The OA data are archived at 6 hour time steps four times per day starting at 00 UT whereas ZPD is usually measured instantaneously at 2 hour time steps starting at 01 UT. In order to obtain ZPD values at the 6 hourly times, the two ZPD measurements before and after the 6 hour time are averaged, i.e. the GPS results are mean values over four hourly intervals (e.g. a ZPD value at 12 UT is the average of the measurements at 11 UT and 13 UT). If only one of these two ZPD measurements is available, it alone represents the 6 hour time.

2.2. From gridded IWV values to point values at the station locations

There are several reasons why the GPS derived IWV data cannot be compared directly with the IWV data from the OA. First they are averaged over different areas (GPS by some 100 km^2 and OA over an area of 10000 km^2). Second, the heights of the GPS stations usually do not agree with the topography used in the OA. Thus, it is necessary to interpolate not only horizontally but also vertically the OA IWV to the position of the GPS station.

The horizontal interpolation of all OA values used, e.g. IWV or model height h, to a station coordinate χ_s is done by a weighted linear interpolation from the surrounding four gridboxes with the centre coordinates χ_i. This horizontal interpolation yields values that represent the OA quantities at the horizontally interpolated OA model surface height.

In order to compare the horizontally interpolated OA IWV values to the GPS derived IWV values, they have to be vertically interpolated from the model surface height to the GPS station height, more precisely the IWV difference between the model surface height and GPS station height has to be estimated. It is assumed that the mean relative humidity of the two lowest OA model levels (j = 1, 2) is representative for the atmospheric layer near the surface, especially at the station height h_S and the model surface height $h(\chi_S)$. As only the specific humidity q is stored in the OA archive at model levels, the relative humidity r for both layers j with the pressure p_j has to be computed using Eq. (7).

$$r_j = \frac{p_j \cdot q_j}{0.622 \cdot e_{S,j}} \tag{7}$$

The saturated water vapour pressure e_S is derived from the model level temperature T_j according to an empirical deduction from the Clausius-Clapeyron equation, e.g. as given by *Holton* (1992).

$$e_{S,j} = 6.107 \cdot e^{19.83 \cdot \frac{T_j - 273.15}{T_j}} \tag{8}$$

Using Eq. (7) and Eq. (8), the specific humidities $q(h_S)$ at station height and $q(h(\chi_S))$ at model surface height can be obtained from

$$q(h) = \frac{q_1 + q_2}{2} \cdot \frac{0.622 \cdot e_S(T(h))}{p_s(h)} \tag{9}$$

For $p_S(h_S)$, the observed surface pressure is used. The model temperature T at station height and the model surface height is computed from the temperature T_1 of the lowest model level by assuming that the temperature lapse rate Γ (= $\partial T/\partial h$) between the two lowest model levels is representative for the atmospheric layer near the surface.

$$\Gamma = \frac{T_2 - T_1}{h_2 - h_1} \tag{10}$$

With $h_1 < h_2$, it may happen on a few occasions that $T_2 > T_1$. Then, the lapse rate would be positive which would cause an erroneous computation of the model IWV correction to the GPS station height. In these cases a standard lapse rate of -0.65 K / 100 m typical for wet adiabatic conditions is assumed. The heights h_j of the two model levels are computed using the barometric height formula. Finally, the adjustment of the OA IWV to the GPS station height is obtained by the integration of q over the height difference between the GPS station and the model surface. Here, linearity is assumed in the vertical distribution of q between the two heights.

$$IWV_{OA} = IWV(\chi_S) + \frac{q(\chi_S) + q(h_S)}{2} \cdot (h(\chi_S) - h_S) \tag{11}$$

2.3. Usage of surface pressure

In order to determine IWV with an accuracy of 1 mm or less the surface pressure used in Eq. (2) requires an accuracy of 1 hPa or less. Unfortunately, surface pressure measurements are available only at a limited amount of GPS stations. Thus, surface pressure has to be obtained from a different location.

Originally, it was tried to use horizontally and vertically shifted surface pressure values of the OA. The idea was that these shifted pressure values at each station may have a constant bias to observed values so that only pressure measurements for a short period would be necessary to assign a fixed model surface pressure bias to each GPS station. This hypothesis was tested at the GPS stations where surface pressure is measured simultaneously. Here, the four months of January and July in 2000 and 2001 were considered. For the majority of the stations the OA surface pressure deviates by more than 3 hPa (for some stations the deviation is considerable larger) from the observations. For this reason the OA surface pressure cannot directly be used to derive IWV from the ZPD measurements.

Then, it was investigated if the deviations between the OA values and the observations are constant in time or at least within a season for each station. In this case a constant OA bias correction could be assigned to each station to estimate the surface pressure at the station from the OA values. But it turned out that the pressure bias is not only dependent on the season but also varies between the years with deviations larger than 1 hPa. Therefore, the assignment of a fixed model pressure bias to each station was ruled out.

Instead we decided to use surface pressure from synoptic stations of the WMO network which are located close to the GPS stations. For each GPS station below 500 m without pressure observations, at least one WMO station was assigned within a 100 km radius where it is assumed that the surface pressure does not differ significantly. For some stations, this assumption may be not valid, but these stations can probably be identified by the methods described in section 3.3.

IWV data can only be achieved every 6 hours (cf. section 2.1) when ZPD and pressure measurements are available at the same time. In the four months considered in the present study, GPS measurements and near-by pressure observations are available for about 120 stations of the IGS global network.

As the WMO stations are usually at a different height than the GPS stations, the surface pressure measurements have to be interpolated to the GPS station height. If surface pressure $p_s(h_{WMO})$ and mean sea level pressure p_0 are available at a 6 hour time step, Eq. (12) is used for the computation of $p_s(h_S)$ which is derived from the barometric height formula by assuming the fraction between the two bulk temperatures at GPS height and WMO height is close to one.

$$p_s(h_S) = p_0 \cdot \left(\frac{p_s(h_{WMO})}{p_0}\right)^{\frac{h_S}{h_{WMO}}} \tag{12}$$

If only p_0 and the bulk temperature are available, the barometric height formula is used directly (Eq. (13)) to compute $p_s(h_S)$.

$$p_s(h_S) = p_0 \cdot e^{-g \cdot \frac{h_S}{R_L \cdot T_v}} \tag{13}$$

If only $p_s(h_{WMO})$ and the bulk temperature are available, Eq. (14) is used which is derived from Eq. (13).

$$p_s(h_S) = p_s(h_{WMO}) \cdot e^{g \cdot \frac{h_{WMO} - h_S}{R_L \cdot T_v}} \quad (14)$$

2.4. Uncertainty of GPS derived IWV

Uncertainties in the GPS derived IWV are mainly caused by errors related to the measurements of ZPD and surface pressure. If surface pressure is not measured at the GPS station, additional uncertainty is introduced by the horizontal distance and vertical interpolation to the GPS station. The uncertainty related to the vertically integrated mean temperature within an atmospheric column taken from the OA is found to be rather small.

Uncertainties in IWV caused by variations in ZPD and surface pressure are almost independent of IWV. A variation of 1 mm in ZPD corresponds to about 0.15-0.16 mm in IWV, a variation of 1 hPa in the surface pressure corresponds to about 0.33-0.37 mm in IWV. As mentioned above, the effect of variations in vertically integrated mean temperature on the IWV values is less than for ZPD and the surface pressure. Uncertainties induced by temperature variations depend also on the absolute amount of IWV. An uncertainty of 5 K corresponds to 1.7-2.0% in IWV.

Table 1. Uncertainty in GPS derived IWV due to zonal path delay measurements at locations with collocated GPS receivers

ΔIWV_{bias} is the mean difference in daily IWV bias between the two stations (1^{st}-2^{nd}) in mm. IWV_{GPS} is the mean daily GPS derived IWV of the two stations in mm. ΔIWV_r is fraction ΔIWV_{bias} divided by IWV_{GPS} in %.

Stations	Height	Variable	Months considered			
			Jan. 2000	July 2000	Jan. 2001	July 2001
NRC1 /	131.45 m	ΔIWV_{bias}	0.038	-0.246	0.061	0.197
NRC2		IWV_{GPS}	4.876	25.632	6.580	24.783
		ΔIWV_r	0.8 %	-1.0 %	0.9 %	0.8 %
NYA1 /	52.01 m	ΔIWV_{bias}	0.237	-0.693	0.144	-0.378
NYAL	46.27 m	IWV_{GPS}	3.405	11.347	3.590	12.208
		ΔIWV_r	7.0 %	-6.1 %	4.0 %	-3.1 %
TRO1 /	107.45 m	ΔIWV_{bias}	0.404	--	0.680	-0.013
TROM	101.82 m	IWV_{GPS}	7.101	18.270	7.396	18.859
		ΔIWV_r	5.7 %	--	9.2 %	-0.1 %
YAR1 /	266.83 m	ΔIWV_{bias}	--	0.059	--	-0.013
YAR2		IWV_{GPS}	27.809	15.343	25.054	13.943
		ΔIWV_r	--	0.4 %	--	-0.1 %

An indication of the actual uncertainty induced by the ZPD measurements is given by Table 1 Here, co-located GPS stations are shown which indicate an inherent accuracy of less than 0.7 mm. Note that it was not feasible to compare the GPS derived IWV values of two co-located stations directly as the days with ZPD measurements mostly do not agree for these stations in the four months considered. Therefore the IWV biases are compared.

Uncertainty related to the use of the WMO surface pressure measurements is given by Table 2. Here, a few randomly selected stations are listed where two (3 for UPAD) WMO stations exists at similar distances close to the same GPS station. Table 2 shows that the absolute uncertainty in IWV caused by the pressure interpolation is 0.5 mm or smaller (except for BAKO). This corresponds to a pressure uncertainty of about 1 hPa or smaller. For many stations this uncertainty is smaller, especially if the pressure is measured close to the GPS station.

Table 2. Uncertainty in GPS derived IWV due to surface pressure measurements (using different WMO stations to get the pressure)

ΔIWV_{bias} is the mean difference in daily IWV bias between the two stations (1^{st}-2^{nd}) in mm. For UPAD, the differences are 1^{st}-2^{nd}, 1^{st}-3^{rd} and 2^{nd}-3^{rd}, respectively. IWV_{GPS} is the mean daily GPS derived IWV of the two stations in mm. ΔIWV_r is fraction ΔIWV_{bias} divided by IWV_{GPS} in %.

Stations		Distance to GPS station		Variable	Months considered			
		Height	Horizontal		Jan. 2000	July 2000	Jan. 2001	July 2001
ALBH	1	-7.1 m	29.2 km	ΔIWV_{bias}	--	--	0.110	-0.404
	2	-4.1 m	31.7 km	IWV_{GPS}	10.310	23.308	11.399	20.193
				ΔIWV_r	--	--	1.0 %	-2.0 %
BAKO	1	-97 m	36.1 km	ΔIWV_{bias}	0.660	-2.357	-0.785	-1.347
	2	-135 m	34.3 km	IWV_{GPS}	57.093	43.798	56.783	40.864
				ΔIWV_r	1.2 %	-5.4 %	-1.4 %	-3.3 %
GRAZ	1	+42.9 m	6.8 km	ΔIWV_{bias}	--	--	-0.251	-0.167
	2	-143.1 m	8.7 km	IWV_{GPS}	6.829	22.441	10.027	25.648
				ΔIWV_r	--	--	-2.5 %	-0.7 %
KIRU	1	-1.1 m	79.7 km	ΔIWV_{bias}	0.261	-0.103	0.343	0.089
	2	+106.9 m	81.1 km	IWV_{GPS}	4.953	18.778	6.134	18.063
				ΔIWV_r	5.3 %	-0.5 %	5.6 %	0.5 %
LAMA	1	-22.2 m	21.7 km	ΔIWV_{bias}	0.461	0.317	0.049	0.229
	2	-49.2 m	49.6 km	IWV_{GPS}	8.807	23.979	9.121	30.654
				ΔIWV_r	5.2 %	1.3 %	0.5 %	0.7 %
TRO1	1	-97.5 m	2.4 km	ΔIWV_{bias}	0.357	0.474	0.563	--
	2	+2.6 m	1.5 km	IWV_{GPS}	6.550	18.445	7.303	18.846
				ΔIWV_r	5.5 %	2.6 %	7.7 %	--
UPAD	1	6.4 m	35.3 km	ΔIWV_{bias}	0.339 -0.099 -0.438	0.451 -0.127 -0.579	0.314 0.263 -0.051	0.452 -0.100 -0.551
	2	13.4 m	33.3 km	IWV_{GPS}	7.981 7.788 7.995	26.435 26.418 26.154	14.013 13.959 13.942	31.886 31.674 31.840
	3	-33.6 m	37.0 km	ΔIWV_r	4.2 % -1.3 % -5.5 %	1.7 % -0.5 % -2.2 %	2.2 % 1.9 % -0.4 %	1.4 % -0.3 % -1.7 %

The values obtained from Table 1 and Table 2 agree quite well with the known quality of GPS derived IWV (*Bengtsson et al.,* 2002a), which have biases and standard deviations in comparisons to collocated instruments like water vapour radiometers or radiosondes as well as to numerical weather models in the range of 0.5 to 1.5 mm IWV. The expected quality is generally higher in mid-latitudes and lower in the ionospheric active regions near the equator.

For stations where there are large height differences between the GPS station and the WMO pressure measurements the IWV uncertainty tends to be larger. This is the case, for example, for the GPS station MONP in California (not shown) with a large height difference between WMO (9 m) and GPS (1852 m) station. This introduces at several occasions errors in the GPS derived IWV causing negative values in July 2000, January and July 2001 (all negative IWV values were set to Zero for the comparison to OA values in section 3). In January 2000 when the pressure was measured directly at the GPS station no negative values occurred.

3. Applications of GPS derived IWV

A comprehensive data-assimilation system generates a continuous evolution of the state of the atmosphere (temperature, wind, moisture and surface pressure) by combining observations from different observing systems with the information available in the model. The state of the system does not only depend on observations from previous times but also in the way observations are combined according to the physical and dynamical constraints enforced by the model equations. In that respect the model and the data-assimilation algorithms act as a filter on the observations, a fact which must be considered when comparing observations with analysed data. The model data are also limited by the numerical resolution of the model and the way orographical obstacles and coast lines are resolved by the model. However, the intercomparison is restricted to the integrated water vapour averaged over 4 hours and furthermore the ECMWF model has a very high vertical (some 35 tropospheric levels) and horizontal resolution (T 511). Consequently we believe that the model is capable to resolve water vapour so to be consistent with the GPS derived IWV. As we will see below this is also the case.

The fact that we have carried through the intercomparison for two winter and two summer months from two different years gives us the possibility to evaluate the differences of the analysed and observed IWV in a comprehensive way. If both data sets agree such that both the standard deviation of daily differences (SD) as well as the monthly averaged difference (bias) are small we may conclude that both the GPS derived values and analysed fields are correct in particular if this is the case for all the four months. In fact as we will see there are several stations that fall in this category. On the other hand if both SD and bias difference are large any of the data sets or both can be wrong and no firm conclusion can generally be drawn. In the case when the bias is large and the SD is small then either the observations or the analyses can be systematically biased. If this is the case for both winter and summer months, most likely the observations are biased since model calculated IWV seldom are equally erroneous in every weather situation. Finally, in the case when the bias is small and the SD large we may assume that the analysed data are likely to be in error, since the quality of the GPS measurements is time-independent, while the quality of the analysed IWV depends on the weather situation.

Section 3.1 presents the overall comparison between the GPS derived IWV values and the OA IWV. This comparison gives a good example on how GPS derived IWV values can be used to validate simulated IWV values. But they also can be used to identify errors or problems in the observations of ZPD and surface pressure. This includes errors in the data itself (section 3.2), e.g. erroneous outlier in the measured time series, as well as systematic errors that affect all IWV values of a specific station (section 3.3). Consequently, stations with large systematic errors in the GPS derived IWV values were blacklisted and not used for the validation of the OA IWV in section 3.1.

3.1. Validation of OA IWV distribution

In general, the OA IWV agrees well with the GPS derived values and both bias and SD are small (Figure 2 and 3). Note that the stations are located all around the world, including regions with high synoptic variance. On a few occasions it can be seen that the OA misses an event at a specific station, e.g. at the African station NKLG in July 2000 (Figure 3d) where a IWV peak shown in the GPS derived IWV around the 21st day does not occur in the OA. Such cases contribute to a larger SD while the bias remains small.

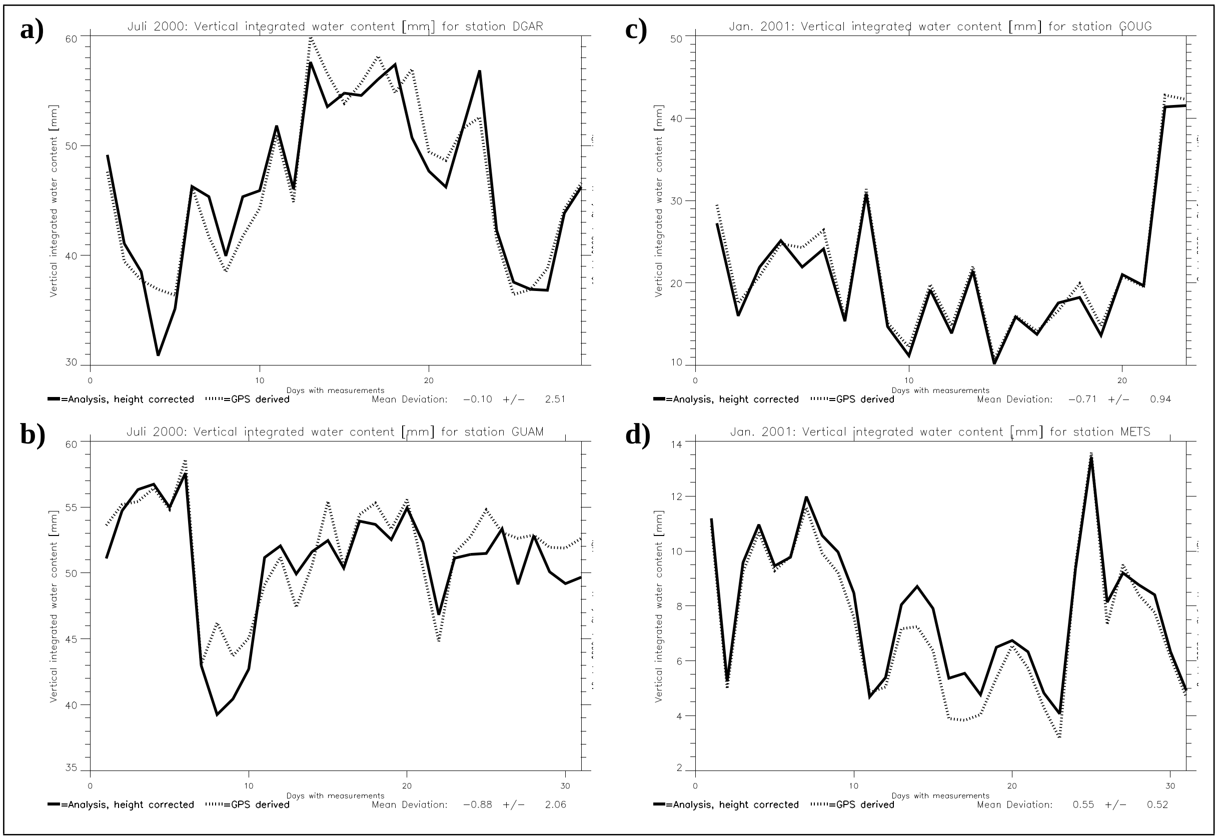

Fig. 2: GPS derived (dotted) and OA (solid) IWV for July 2000 at station **a)** DGAR (Indian Ocean), **b)** GUAM (West Pacific), and for January 2001 at station **c)** GOUG (South Atlantic), **d)** METS (Finland).

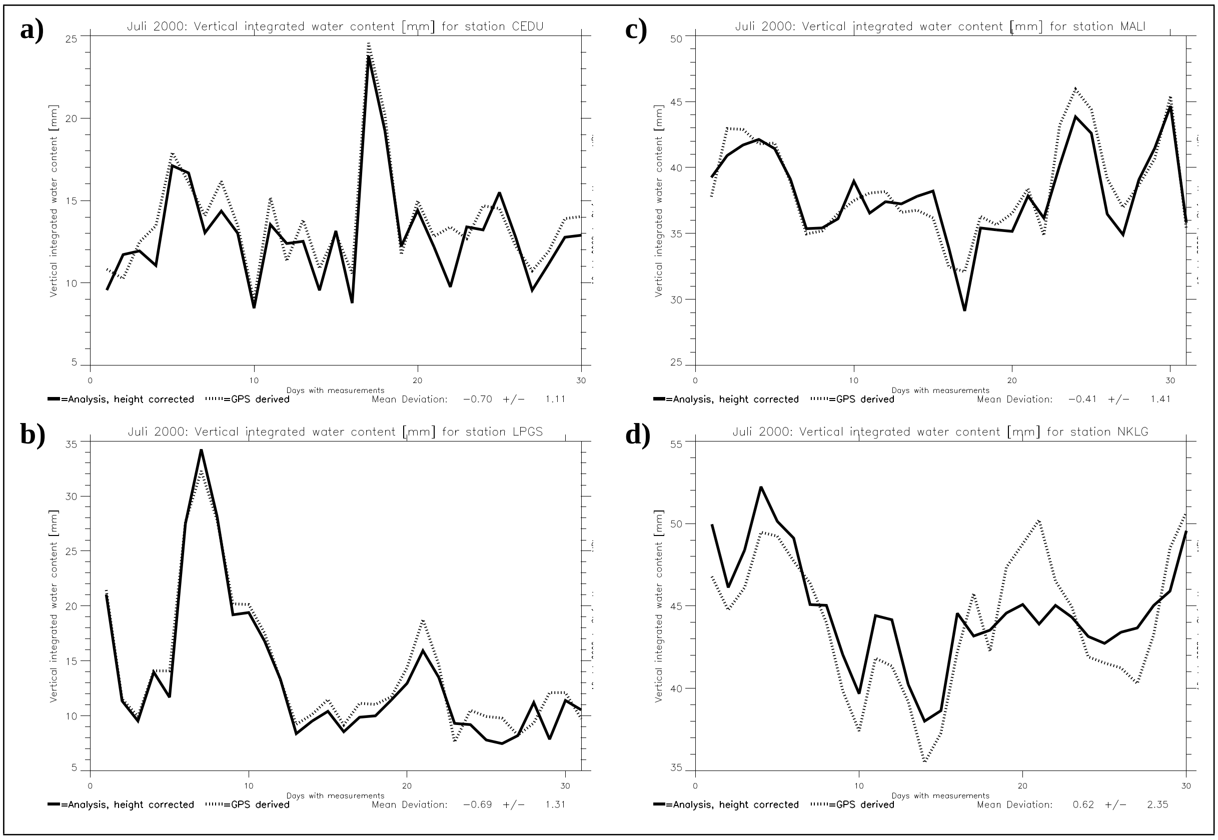

Fig. 3: GPS derived (dotted) and OA (solid) IWV for July 2000 at station **a)** CEDU (S Australia), **b)** LPGS (Argentina), **c)** MALI (Kenya), **d)** NKLG (Gabon).

Table 3 summarizes the bias percentages for several regions where the biases are just averaged over the stations within each region. The winter dry bias of the OA over central USA/Canada and Siberia clearly shows up while no bias occurs in the summer. For the southern parts of Siberia, the general distribution of biases in July (not shown) even show a small OA wet bias. The large opposite biases in the central Asian desert region may not be significant as only two stations are located here. But taking the July bias over Saudi Arabia into account it seems that the OA tends to overestimate IWV over northern hemisphere dry regions in July. Over Australia and surrounding areas there is a weak tendency of the OA to underestimate IWV. This is supported by the general distribution of biases in this area (not shown) where small dry biases (larger than 1%) exist for the majority of stations (11 in January, 9 in July).

Table 3. Regional station averages of fractional bias (ΔIWV_{bias} divided by IWV_{GPS}) in %.

Region	Latitude	Longitude	January 2000/01		July 2000/01	
			N_{Stat}	Bias [%]	N_{Stat}	Bias [%]
North America	30˚N-90˚N	170˚W-50˚W	25	-3.02	22	-0.92
Central USA/Canada	35˚N-65˚N	120˚W-70˚W	12	-13.74	12	0.26
Central America	5˚N-30˚N	115˚W-55˚W	4	-0.91	4	-1.44
South America	55˚S-10˚N	85˚W-30˚W	3	-2.27	3	-3.10
Southern Africa	40˚S-5˚N	5˚E-55˚E	3	0.75	4	-4.25
Europe	35˚N-75˚N	15˚W-45˚E	34	1.01	35	0.49
Baltic Sea catchment	50˚N-70˚N	5˚E-40˚E	15	-0.39	15	0.16
Central Europe	42˚N-55˚N	5˚E-30˚E	15	1.37	16	0.78
Mediterranean Sea	30˚N-45˚N	10˚W-40˚E	15	-0.66	17	4.07
Siberia	50˚N-80˚N	60˚E-180˚E	7	-19.86	9	-0.14
Central Asian Deserts	30˚N-50˚N	55˚E-110˚E	2	-23.93	2	23.40
Saudi Arabia	10˚N-35˚N	30˚E-60˚E	5	-1.08	6	7.19
Southern Asia	0˚N-35˚N	60˚E-150˚E	5	2.03	4	0.03
Tropical Ind./Pac. Ocean	15˚S-15˚N	60˚E-180˚E	8	-2.38	7	-1.29
Australia	45˚S-10˚S	110˚E-150˚E	7	-2.79	8	-2.17
Australia + surroundings	60˚S-0˚S	90˚E-180˚E	12	-4.10	12	-2.41

In order to analyse the OA dry bias over North America in the winter in more detail we have compared the vertical humidity profiles of the OA with radiosonde measurements for January and July 2001 for several locations. In contradiction to the results found before this comparison shows that the OA humidity profiles are wetter than the radiosonde profiles for most of the radiosonde locations in both months which may indicate an OA wet bias in the humidity.

As an example, the station NLIB in Iowa is considered in Figure 4. For January 2001 (Figure 4a), a large dry bias is shown for the OA which is about 4 times larger than the SD. But in July 2001 (Figure 4b) the relatively good agreement (small bias, small SD) of OA and GPS derived IWV indicates (cf. section 3) that both IWV values are good. Atmospheric humidity measurements from the Quad City (WMO no. 74455) radiosonde located in the same region are drier than the corresponding OA values (Figure 5). As we found the OA IWV values to be accurate in July 2001 this indicates a dry bias of the radiosonde which probably occurs independently of the season. Therefore we conclude that a general dry bias of the radiosondes over North America exists which would mean that the radiosondes are also too dry in the winter so that they cannot be used to verify the IWV values in January 2001. This conclusion is supported by *Zipser and Johnson* (1998) who identified a systematic and significant dry bias in radiosonde humidity data from Vaisala radiosondes that are widely used over North America. Currently, approximately 51% of global operational radiosonde stations and 63% of U.S. stations use Vaisala radiosondes (*Wang et al.*, 2002).

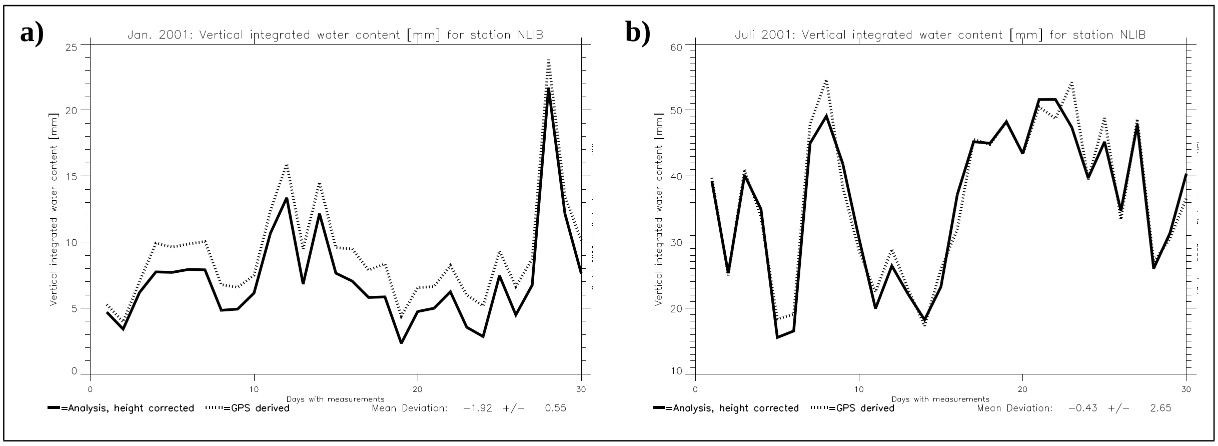

Fig. 4: GPS derived (dotted) and OA (solid) IWV at station NLIB (Iowa) for **a)** January 2001, **b)** July 2001.

Since the radiosonde data are assimilated in the generation process of the OA this may also imply that the radiosonde data are the cause of the overly dry IWV in the OA. However, it has to be clarified why this only happens in the winter. Here, a repetition of the data assimilation without assimilation of atmospheric moisture data with the ERA40 system (*Bengtsson et al.*, 2002b) for January 2001 may help to clarify this question.

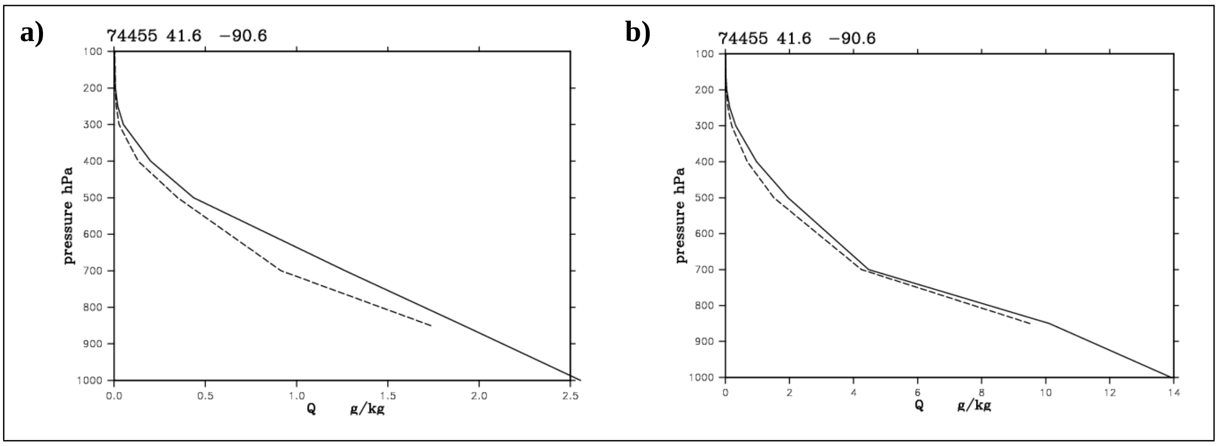

Fig. 5: Vertical humidity profiles from radiosonde measurements (dashed) and OA (solid) at the Quad City station (WMO no. 74455) in Iowa for **a)** January 2001, **b)** July 2001.

3.2. Identification of erroneous measurements

The daily time series of IWV_{GPS} and IWV_{OA} are used to identify erroneous data either in the *ZPD* or in the surface pressure measurements. If there are outliers in IWV_{GPS} that are not found in IWV_{OA} this may suggest errors in the GPS data. During the present study the data files containing the *ZPD* and the surface pressure measurements were manually looked up for the days of the suspicious data and several erroneous measurements could be eliminated from the data records with this method. For later applications, it is planned to apply an automatic method similar to what is used in the quality control system in the ECMWF data assimilation system (*Hollingsworth et al.*, 1986).

If substantial differences occur in the IWV bias for different months and/or years for one station, this is another indication of a possible error in the GPS data. In this way, the GPS station BRUS (Brussels) was identified to have severely biased pressure measurements in January 2000 and before 19 July 2000.

3.3. Identification of suspicious GPS stations

If the mean IWV bias between IWV_{GPS} and IWV_{OA} for a station is larger than its SD, this indicates a systematic error either in the ZPD measurements or in the surface pressure and its interpolation. This includes possible errors in the height that is assigned to the GPS or the WMO station. Table 4 summarizes suspicious stations where the IWV bias is larger than the SD error in at least 3 of the 4 months. These stations are investigated in more detail in the following.

Table 4. Selected stations with a daily IWV bias larger than its standard deviation SD (Bias is given as multiple of SD, p_S = height where surface pressure is measured, GPS = height at GPS station, OA = OA model surface height at GPS station location). For HFLK p_S was measured at the GPS station only in 1 of the 4 months, and taken from a neighbouring synoptic station in the other 3 months.

Station	Location	Bias [SD]	Height above sea level [m]			Hor. Distance p_S-GPS [km]
			p_S	GPS	OA	
ASC1	Trop. Atlantic	+1.1	79	92	1	2.3
CAS1	Antarctica	-3.5	42	37	342	0.6
DAV1	Antarctica	-4.0	22	27	457	0.8
EISL	S Pacific	-1.2	51	153	1	5.4
HFLK	Innsbruck	+1.4	2336 / 593	2336	1176	0. / 5.8
HOFN	Island	-3.4	21	50	430	3.8
KELY	Greenland	-4.9	53	227	621	11.2
KODK	Alaska	-8.0	6	21	112	0.2
KOKB	Hawaii	+1.4	1147	1147	11	0.0
LHAS	Himalaya	+1.6	3661	3661	4851	0.0
MAW1	Antarctica	-2.8	16	32	585	0.6
MCM4	Antarctica	-2.4	24	154	220	1.3
NPLD	London	-10.2	31	402	9	23.7
PERT	SW Australia	+1.3	20	45	182	16.5
THTI	S Pacific	+1.4	2	38	9	3.2
THU1	Greenland	-3.6	62	57	305	1.1
UPAD	Padua, I	+1.6	46	40	384	35.5
UPAD	Padua, I	+1.2	53	40	384	33.3
UPAD	Padua, I	+1.3	6	40	384	37.0

The first group concerns stations in regions where sharp gradients exist in meteorological parameters including IWV (particularly stations located close to steep topography gradients), which cannot be properly represented by the ECMWF model. This is the case for several stations at the Antarctic (CAS1, DAV1, MAW1, MCM4) and Greenland (KELY, THU1) coasts. As an example Figure 6 shows results from the station HOFN (Iceland) situated at the eastern coast near Mount Vatnajökull (2119 m). The IWV_{OA} are systematically smaller than the IWV_{GPS}, since the model is likely to represent conditions over the large glacier and not the conditions at the station. The situation is similar at the coastal Antarctic stations (and also for KELY) which are located close to steep topography gradients (reaching up to 1000-3000 m). Here, an ECMWF model problem related to the Antarctic region might also play a role. For THU1, problems related to steep topography gradients should be less pronounced so that it may well be that the OA model does not capture everything in this region.

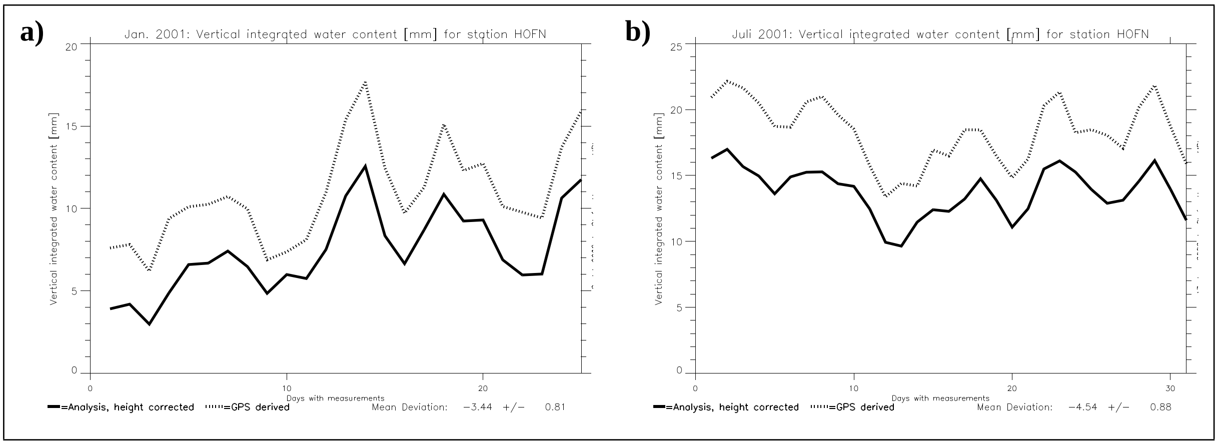

Fig. 6: GPS derived (dotted) and OA (solid) IWV at station HOFN (Iceland) for **a)** January 2001, **b)** July 2001.

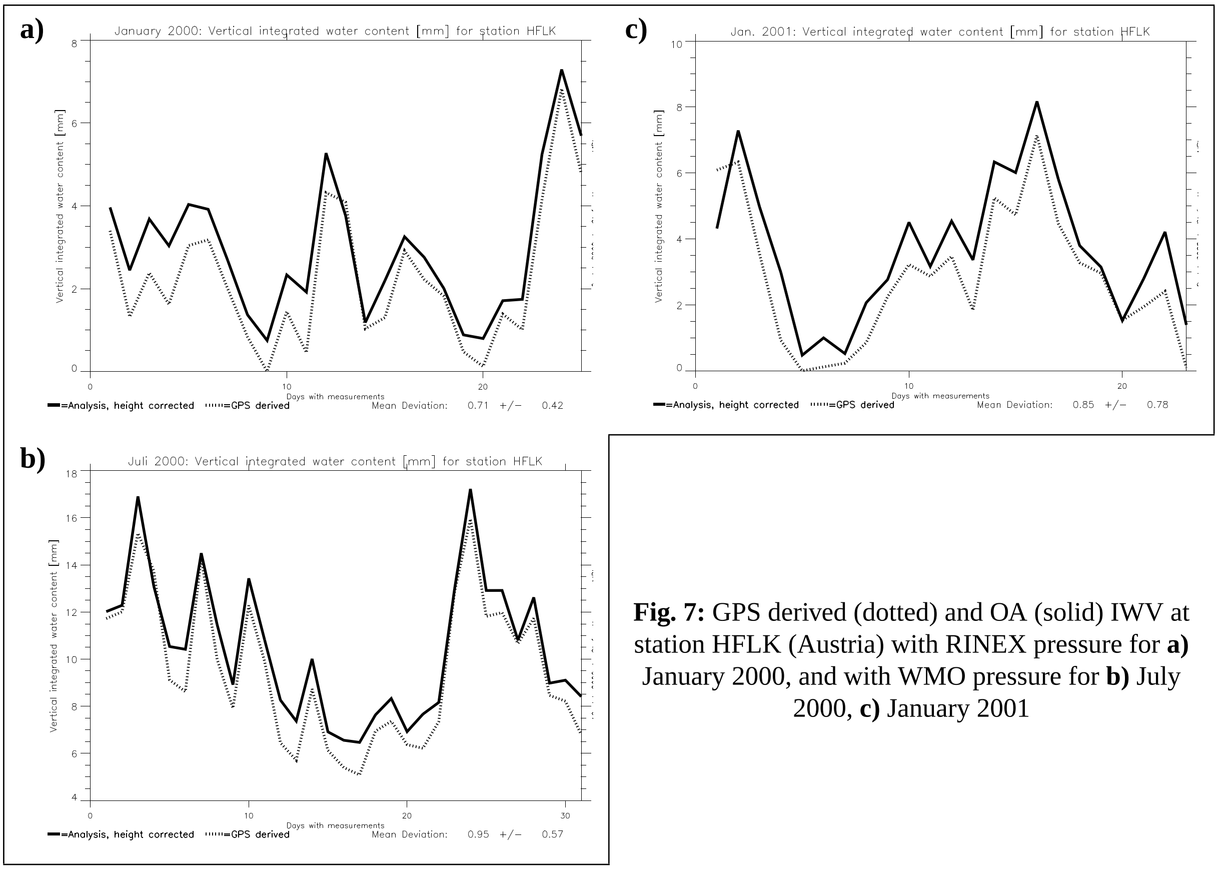

Fig. 7: GPS derived (dotted) and OA (solid) IWV at station HFLK (Austria) with RINEX pressure for **a)** January 2000, and with WMO pressure for **b)** July 2000, **c)** January 2001

The second group concerns stations where the height difference is very large between the GPS station and the OA surface as it is the case for the stations KOKB and HFLK. The Hawaiian station KOKB is located on a mountain (1147 m) which is not seen by the OA (11 m) so that the meteorological conditions at the mountain cannot be represented in the OA. For the Austrian station HFLK (see Figure 7), it seems that the vertical interpolation of p_S from the WMO station height (593 m) to the GPS station height (2336 m) does not largely influence the systematic error caused by the height difference to the OA (1176 m) since the IWV bias and RMS error are very similar in both cases when the pressure is measured at the GPS station (only in January 2000) or taken from the WMO station (in the other 3 months). The two January plots (Figure 7a and 7c) also show that both the OA and the GPS measurements handle very low atmospheric humidity quite well as the absolute amounts of IWV seem to be at the limit of the measurements itself.

The third group concerns stations where the station height is very high so that the assumption of homogeneity in the boundary layer doesn‘t hold which will cause systematic errors in IWV_{GPS} as well as in $IWV_{OA.}$ This is the case for GPS station LHAS located at a height of 3661 m (OA surface height: 4851 m). Other GPS stations at similar heights were excluded from the present study beforehand.

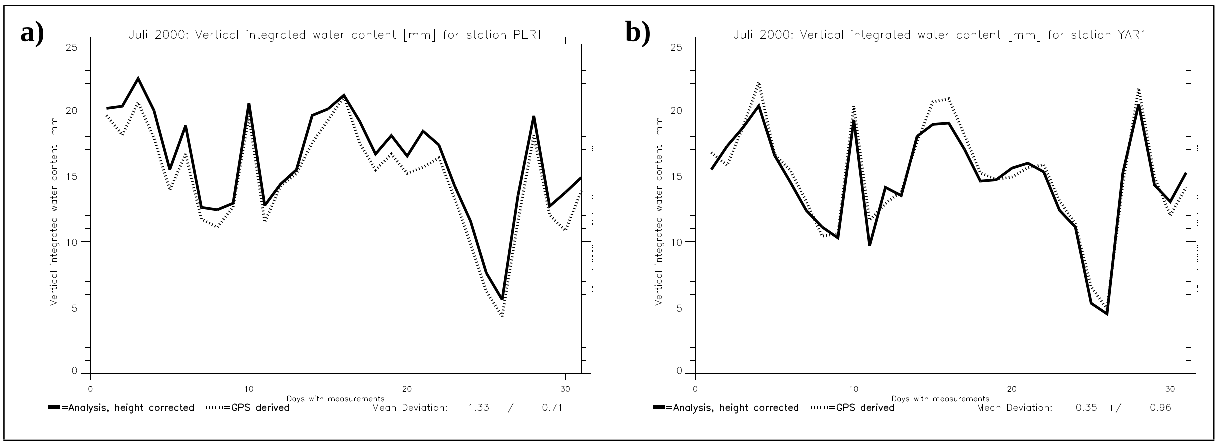

Fig. 8: GPS derived (dotted) and OA (solid) IWV for July 2000 at the SW Australian stations **a)** PERT, and **b)** YAR1.

The fourth group concerns stations which have systematic errors in the measured data itself. This seems to be the case for NPLD, KODK, PERT and UPAD. For NPLD, most certainly an erroneous height (402 m) is assigned to the GPS station as the station is located near London. General station errors (GPS or WMO) seem to be the case for KODK (located on Kodiak Island in the Gulf of Alaska) and PERT. Especially for the latter station this assumption seems to be justified as the IWV biases are generally quite small for Australia. This is confirmed by the comparison of the IWV curves at PERT and the neighbouring station YAR1 in Figure 8. For YAR1, IWV_{OA} and IWV_{GPS} agree quite well with a slight underestimation of the peaks by the OA while for PERT a positive systematic bias occurs. For UPAD, the systematic error is related to the GPS station as the mean IWV bias (2.09, 1.70 and 1.95 mm) is larger than the mean RMS error (1.34, 1.51 and 1.61 mm, respectively) for all pressure measurements of the 3 WMO stations.

The last group concerns stations where the OA seems to have a problem as it is probably the case for the stations EISL, ASC1 and THTI. Figure 9 shows the IWV at EISL (Easter Island) for all 4 months. From the curves it seems that the OA generally underestimates the peaks of the GPS derived IWV while many IWV minima are located quite close together in the two curves. It might be that the position of the South Pacific convergence zone (SPCZ) is not captured well in the OA. Similar model problems may apply also to ASC1 (Figure 10a and 10b, tropical Atlantic, position of the inner tropical convergence zone) and THTI (Figure 10c and 10d, tropical Pacific, position of the SPCZ).

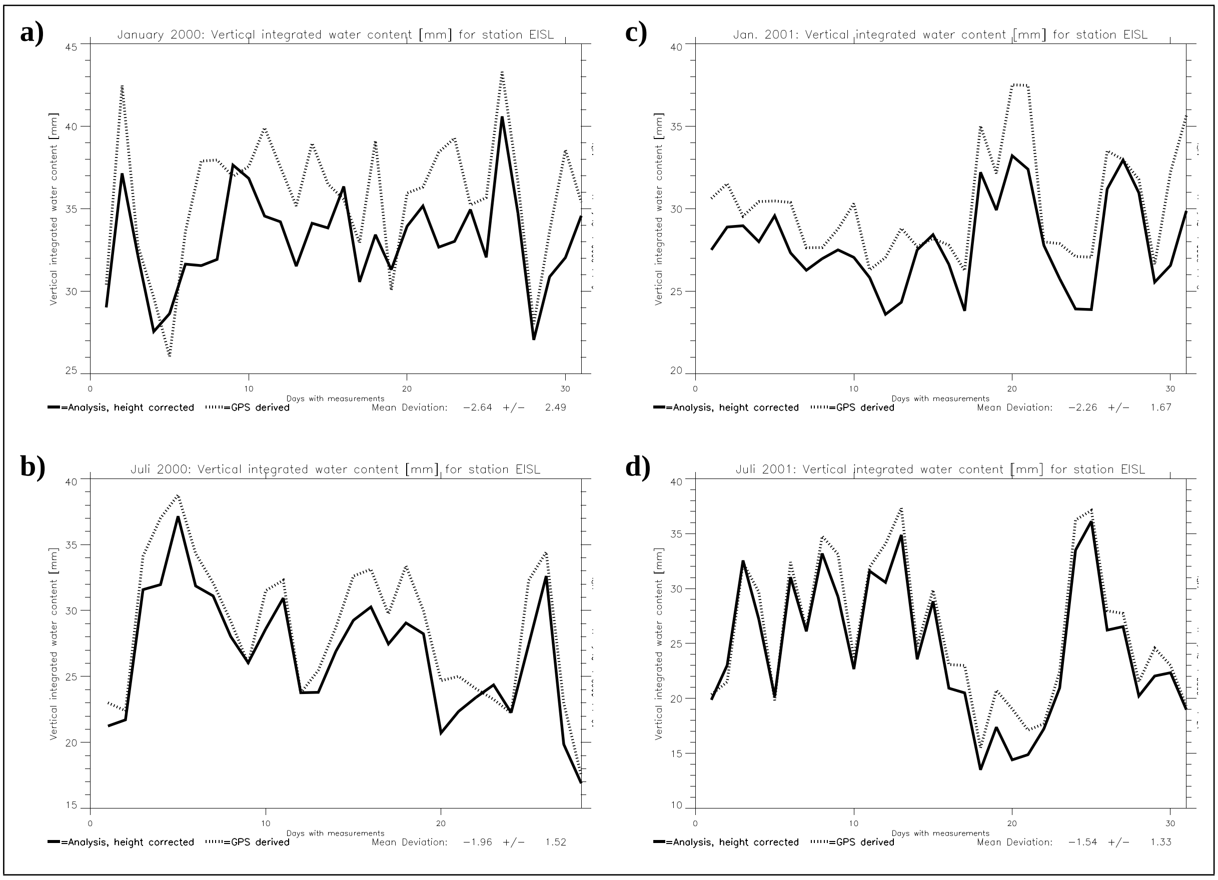

Fig. 9: GPS derived (dotted) and OA (solid) IWV at station EISL (Easter Island) for **a)** January 2000, **b)** July 2000, **c)** January 2001, **d)** July 2001.

Except for ASC1, EISL, HFLK and THTI, all stations included in Table 4 are afflicted with systematic errors so that they must be blacklisted in model validation studies. For studies of long-term changes in the IWV itself these stations can still be used.

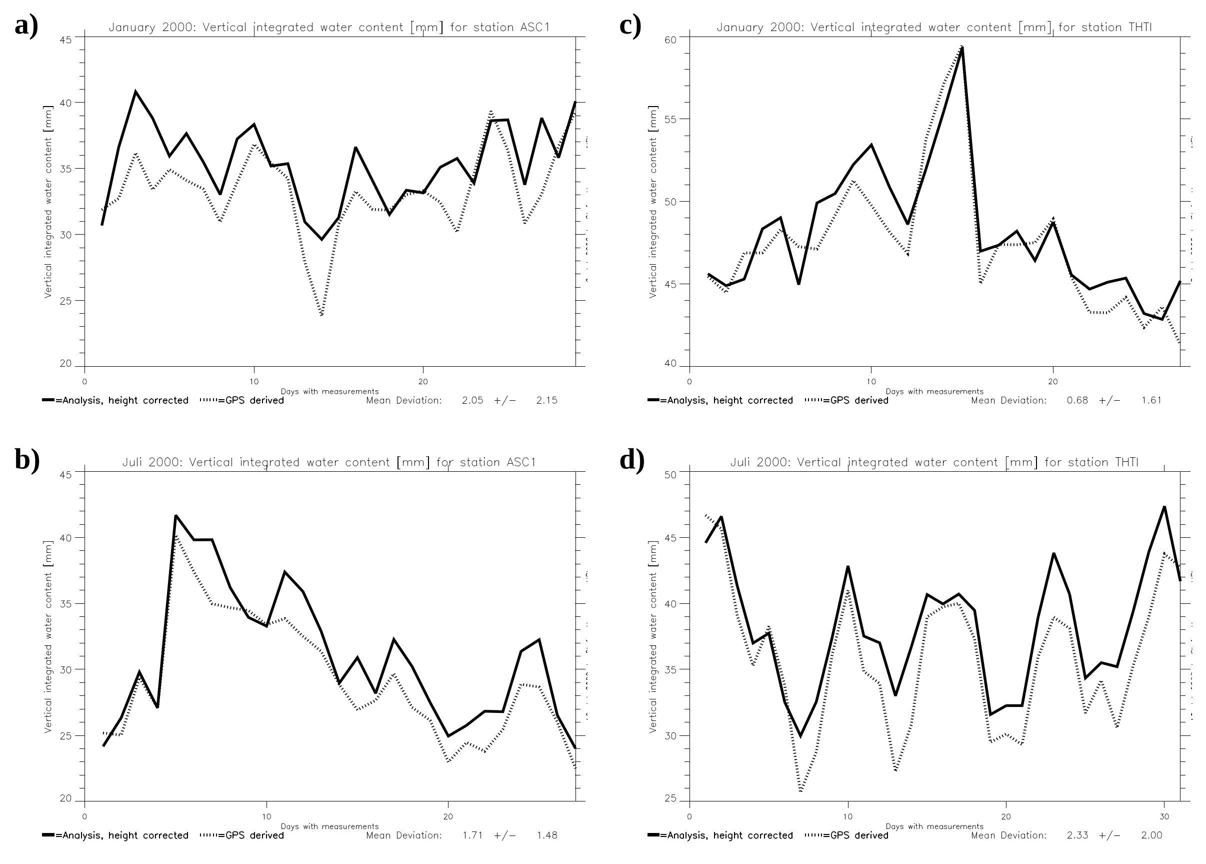

Fig. 10: GPS derived (dotted) and OA (solid) IWV at station ASC1 (Tropical Atlantic) for **a)** January 2000, **b)** July 2000, and at station THTI (Tahiti) for **c)** January 2000, **d)** July 2000.

4. Conclusions and future works

In the current study it was shown that GPS data can be used for the validation of simulated IWV values as well as for quality control of GPS and pressure stations. Uncertainty in the GPS derived IWV is induced by the GPS measurements of ZPD (< 0.7 mm), the use of surface pressure measurements from surrounding areas (≤ 0.5 mm), and the vertically integrated mean temperature taken from the OA, though the sensitivity to errors in the latter is rather small (a variation of 5 K corresponds to an uncertainty of 1.7-2% in IWV). A comparison of GPS derived IWV values to the IWV simulated by the operational analyses of the ECMWF shows that both agree quite well. For most GPS stations the typical behaviour is generally the same for both summer and winter months except for winter data in the interior of US and Eurasia where the modelled IWV is systematically lower than the measured one. Indications are that the assimilation system underestimates IWV in these regions during the winter. As no systematic bias is found in the summer months this supports a dry bias recently found in radiosonde humidity data from Vaisala RS80 radiosondes (*Zipser and Johnson,* 1998). The tendency of small wet biases over northern mid-latitudinal dry regions is a subject for future studies.

We excluded here situations with severe representation problems such as stations located at steep mountain slopes or near major land ice areas such as Greenland or Antarctica, where the model cannot represent the sharp gradients in IWV. In these and other cases it is not unlikely that the surface pressure is incorrect for example due to interpolation errors introduced by an inhomogeneous boundary layer or the GPS station has a wrongly assigned height. *This stresses the urgent need to provide all GPS stations with suitable pressure gauges. It is only then that the GPS data can be useful for monitoring and model validation.* The pressure instruments can be rather inexpensive devices since an accuracy of the order of 0.5 hPa should be sufficient. Using the 4 months considered in this study, it was possible to identify problematic stations with systematic errors in the GPS derived IWV that must be blacklisted in model validation studies. For studies of long-term changes in the IWV itself these stations can still be used.

Based on this preliminary study, it seems that the network of GPS stations suitably extended and equipped with pressure gauges would provide a long-term systematic approach for monitoring atmospheric water vapour. Because of external variations on interannual time scales mainly related to ENSO events such a network should be established for long-term operation. As we have shown in this study atmospheric temperature data of sufficient accuracy can be obtained from operational analyses. These analyses will also serve to check the quality of the GPS stations as we have indicated.

The GPS derived IWV values will further be used to validate the most recent years of the new 40 years re-analyses that is currently produced at ECMWF. Such work is in progress and will also be carried out along the lines used in *Bengtsson et al.* (2002b).

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References

Bengtsson, L. G. Robinson, R. Anthes, K. Aonashi, R. Bingley, P. Cannon, A. Dodson, G. Elgered, G. Gendt, R. Gurney, M. Jitai, N. Latham, C. Marquardt, C. Mitchell, M. Mlaki, J. Nash, D. Offiler, A. Rhodin, P. Silvestrin, R. Ware, R. Watson, W. Wergen (2002a) Meeting Summary: Workshop on the use of GPS measurements for water vapor determination, *Bull. Amer. Met. Soc.*, accepted

Bengtsson, L., K. Hodges and S. Hagemann (2002b) On the determination of the global water cycle from re-analysis data, *Mon. Weather Rev.*, submitted

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

Bevis, M.S., S. Businger, S. Chiswell, T.A. Herring, R.A. Anthes, C. Rocken, and R.H. Ware (1994) GPS meteorology: Mapping zenith wet delays onto precipitable water, *J. Appl. Meteorol.* **33**, 379-386

Businger, S., S. Chiswell, M. Bevis, J. Duan, R. Anthes, C. Rocken, R. Ware, M. Exner, T. Von Hove, and F. Solheim (1996) The Promise of GPS in Atmospheric Monitoring. *Bull. Amer. Met. Soc.* **77**, 5-18.

Davis, J.L., T.A. Herring, I.L. Shapiro, A.E.E. Rogers, and G. Elgered (1985) Geodesy by radio interferometry: Effects of atmospheric modeling errors on estimates of baseline length. *Radio Sci.* **20**, 1593-1607.

Elgered, G. (1993) Tropospheric radio-path delay from ground-based microwave-radiometry. Atmospheric Remote Sensing by Microwave Radiometry, *Wiley*, 215-258.

Gaffen, D.J., M.A. Sargent, R.E. Habermann, and J.R. Lanzante (2000) Sensitivity of tropospheric and stratospheric temperature trends to radiosonde data quality. *J. Climate* **13**, 1776-1796.

Gendt, G (1999) Status Report of the Troposperic Working Group IGS Analysis Center Workshop, 8-10 June 1999, La Jolla, CA, USA in "IGS 1999 Technical Reports", Eds. K. Gowey, R. Neilan, A. Moore, JPL/IGS Central Bureau, Pasadena, CA, November 2000, pp. 375-384

Hall, A., and S. Manabe (1999) The role of water vapor feedback in unperturbed climate variability and global warming, *J. Climate* **12**, 2327-2346.

Held, I.M., and B.J. Soden (2000) Water vapor feedback and global warming. In: *Annual Reviews of Energy and the Environment*, Vol. **25**, 49p.

Hollingsworth, A., D.B. Shaw, P. Lonnberg, L. Illari, K. Arpe, and A.J. Simmons (1986) Monitoring of observation and analysis quality by a data assimilation system. *Mon. Weath. Rev.* **114**, 861-879

Holton, J.R. (1992) An introduction to dynamic meteorology, 3rd ed., *Academic Press, Inc.*, San Diego, California

Rocken, C., R.H. Ware, T. Van Hove, F. Solheim, C. Alber, J. Johnson, M. Bevis, and S. Businger (1993)
Sensing atmospheric water vapor with the Global Positioning System, *Geophys. Res. Lett.* **20**, 2631-2634.

Rocken, C., T. Van Hove, J. Johnson, F. Solheim, R. Ware, M. Bevis, S. Businger, and S. Chiswell (1995)
GPS Storm - GPS sensing of atmospheric water vapor for meteorology, *J. Atmos. Oceanic Technol.* **12**, 468-478.

Saastamoinen, J. (1972)
Atmospheric correction for the troposphere and stratosphere in radio ranging of satellites, Ed.: S.W. Henriksen et al., The Use of Artificial Satellites for Geodesy, *Geophys. Monogr. Ser.* **15**, AGU, Washington, D.C., 247-251.

Schneider, E.K., B.P. Kirtman, and R.S. Lindzen (1999)
Tropospheric water vapor and climate sensitivity. *J. Atmos. Sci.* **56**, 1649-1658

Semenov, V.A., and L. Bengtsson (2002)
Secular trends in daily precipitation characteristics: greenhouse gas simulation with a coupled AOGCM, *Clim. Dyn.* **19**, 123-140

Trenberth, K.E., D.P. Stepaniak, J.W. Hurrell, and M. Fiorino (2001)
Quality of reanalyses in the Tropics, *J. Climate* **14**, 1499-1510

Wang, J., H.L. Cole, D.J. Carlson, E.R. Miller, K. Beierle, A. Paukkunen, and T.P. Laine (2002)
Corrections of humidity measurement errors from the Vaisala RS80 radiosonde - application to TOGA COARE data, *J. Atmos. Oceanic Technol.* **19**, 981-1002

Yuan, L.Y., R.A. Anthes, R.H. Ware, C. Rocken, W.D. Bonner, M.G. Bevis, and S. Businger (1993)
Sensing climate change using the global positioning system, *J. Geophys. Res.* **98**, 14925-14937

Zipser, E.J., and R.H. Johnson (1998),
Systematic errors in radiosonde humidities a global problem? Preprints, *10th Symp. on Meteorological Observations and Instrumentation*, Phoenix, AZ, Amer. Meteor. Soc., 72-73

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