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On the determination of atmospheric water vapor from GPS measurements

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[1] Surface-based GPS measurements of zenith path delay (ZPD) can be used to derive vertically integrated water vapor (IWV) of the atmosphere. ZPD data are collected in a global network presently consisting of 160 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 water vapor column temperature obtained from the European Centre for Medium-Range Weather Forecasts' (ECMWF) operational analyses (OA). For the 4 months of January/July 2000/2001, the GPS-derived IWV values are compared to the IWV from the ECMWF OA, 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 OA of IWV. For most GPS stations, the IWV data agree quite well with the analyzed 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 United States, 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 vapor monitoring system are discussed. *INDEX TERMS:* 1640 Global Change: Remote sensing; 1655 Global Change: Water cycles (1836); 1694 Global Change: Instruments and techniques; 1836 Hydrology: Hydrologic budget (1655); 3337 Meteorology and Atmospheric Dynamics: Numerical modeling and data assimilation; *KEYWORDS:* climate monitoring, precipitable water, water vapor

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1. Introduction

[2] Reliable humidity data are crucial for climate monitoring and prediction. Atmospheric water vapor is the dominating greenhouse gas, and so quantifying the feedback of water vapor in global warming is 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 vapor 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 vapor in the longwave radiation calculations of the Geophysical Fluid Dynamics Laboratory's (GFDL) model in CO_2-doubling experiments reduces the global averaged warming from 3.38 to 1.05 K, meaning a water vapor enhancement factor of 3.2. This is significantly larger than the direct effect of water vapor based on energy balance estimates [e.g., *Held and Soden*, 2000], indicating that water vapor feedback is also crucial for other feedback processes, such as snow, sea ice, and clouds, that also play a significant role.

[3] Water vapor varies considerably in time and space, and the present observing systems are inadequate to monitor water vapor properly [*Gaffen et al.*, 2000]. Satellite observing

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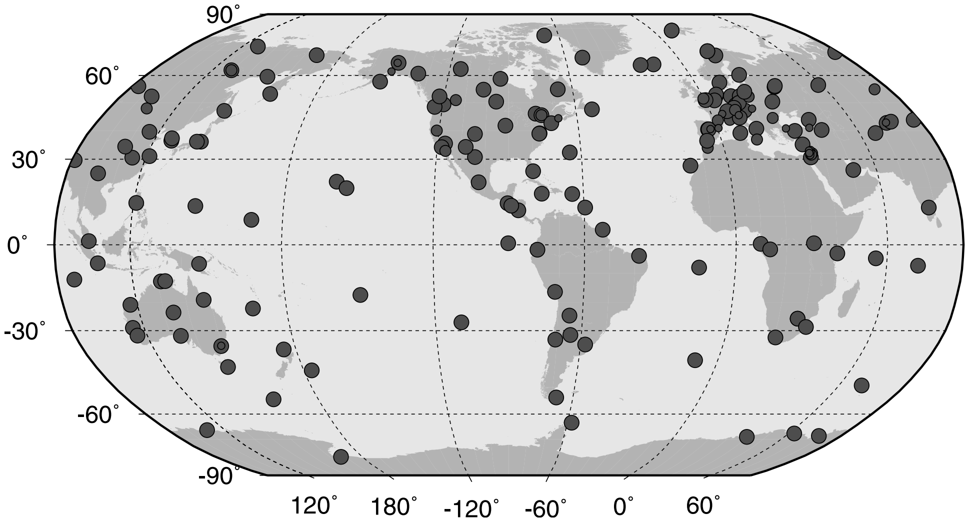

Figure 1. The IGS network of 160 ground-based GPS stations. See color version of this figure in the HTML.

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].

[4] Surface-based GPS 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 vapor are being established all around the world; vertical profiling by satellite occultation techniques is similarly taking place.

[5] With the surface-based technique, dual-frequency signals are collected at the receivers and used to obtain the signal propagation delay due to the atmosphere and thus the integrated water vapor (IWV) 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 while exploring the cause of errors in geodetic measurements [*Davis et al.*, 1985; *Elgered*, 1993].

[6] 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 IWV and their utility in improving near-real-time weather prediction. However, 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.* [2003a] give an overview of these ongoing activities.

[7] As part of the International GPS Service (IGS) a number of countries are collaborating to collect, process, and disseminate data from receivers worldwide. The global network is steadily growing and presently comprises about 300 sites. Since 1997, a tropospheric product has been compiled for a subset of about 160 stations (Figure 1). This product is the zenith path delay (ZPD) of the neutral atmosphere and is available with a delay of 4 weeks. During the GPS data analysis, many analysis centers are performing a least squares adjustment to solve for the ZPD parameters in two hourly bins, which results in a sampling rate of 2 hours centered around the odd hours. The product is generated from submissions from all the IGS analysis centers and therefore has good reliability and an internal consistency on the order of 3-mm ZPD for bias and standard deviation (SD). The consistency between the different analysis centers is at this high level because they are using similar models for the various error sources and, of course, the input GPS data set is the same for each site processed. Rather, different approaches would lead to systematic effects between the analysis centers, which could be on the order of 6-mm ZPD, but not much larger, as comparisons with independent observations have revealed. During history, only a few changes at the analysis centers caused changes in its biases which effect the mean product only at the level of a tenth of a millimeter IWV. Monitoring these biases will allow correcting even for these small values in the future. Even smaller effects can be expected by approximations in the models, like for the antenna phase center variations, and by errors in the satellite orbits (the final IGS orbits have an accuracy of 3–5 cm). The mapping function models have seasonal terms which may introduce seasonal variations in the errors, but the known comparisons with collocated instruments, like water vapor radiometer, have not yet proved these errors to be beyond the millimeter level. Investigations of these effects are beyond the topic of this paper.

[8] For about 40 sites the surface meteorological data are also collected and can be directly used for conversion into IWV. The height difference between sensor and GPS antenna is given and has to be corrected for. A crucial problem is the ongoing pressure sensor calibration of these often remote sites. The presented monitoring can yield an independent check of the pressure sensors.

[9] Recently, IGS has started a pilot project to generate a ZPD product with low latency. Presently, it is generated every 3 hours with a delay of 2 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.

[10] The purpose of this study is to retrieve IWV calculated from the IGS data and to apply a quality control to the IWV for each station by comparing it with the IWV from the European Centre for Medium-Range Weather Forecasts' (ECMWF) operational analyses (OA). The GPS results are taken from the IGS combined tropospheric products, where the estimates of seven centers are combined to get the final ZPD results [*Gendt*, 1999]. The ZPD values are converted into IWV using observed surface pressure and mean atmospheric water vapor column temperature obtained from the ECMWF operational analyses.

[11] The following science questions are addressed:

[12] 1. How well does the ECMWF operational forecasting system analyze IWV as compared to those retrieved from GPS measurements?

[13] 2. To what extent is it possible to separate errors in model-analyzed IWV from IWV obtained from GPS measurements? What are the most likely sources of errors?

[14] 3. What are the long-term requirements for a GPS-based water vapor monitoring system?

[15] If only the determination of possible IWV trends is of interest, an alternative approach would be to work directly with the ZPD measurements and to calculate ZPD data from the corresponding model (e.g., the OA).

[16] The technical methods showing 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 Vapor at the GPS Station Locations

2.1. Calculation of IWV From ZPD

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

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

[18] Following *Yuan et al.* [1993], the ZHD can be written as a function of the surface pressure P_s in hectopascal (in equation (2), a typing error included in the paper of *Yuan et al.* [1993] is corrected. The correct value is 2.279):

$$\mathrm{ZHD} = (2.2790 \pm 0.0024)\frac{P_s}{f(\lambda, h)} \approx (2.2790 \pm 0.0024)P_s, \tag{2}$$

where $f(\lambda, h)$ is a factor close to unity that accounts for the variation in gravitational acceleration, with latitude λ and height h in kilometers [*Saastamoinen*, 1972]:

$$f(\lambda, h) = 1 - 0.0026 \cos\left(2\lambda\frac{\pi}{180}\right) - 2.8 \times 10^{-4}h. \tag{3}$$

[19] The ZWD depends upon the vertical distribution of water vapor and can be directly related to IWV by equation (4).

$$\mathrm{IWV} \times \rho_{\mathrm{H_2O}} = \kappa \times \mathrm{ZWD}, \tag{4}$$

with a proportional coefficient κ yielded from

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

where

$$c_1 = (3.776 \pm 0.030)10^5\mathrm{K}^2\,\mathrm{hPa}^{-1}$$

and

$$c_2 = (17 \pm 10)\mathrm{K}\,\mathrm{hPa}^{-1}.$$

Here R_V is the specific gas constant for water vapor (461.45 J kg^{-1} K^{-1}) and ρ_{H_2}O is the density of water (1000 kg m^{-3}). T_m is the vertically integrated mean temperature within an atmospheric water vapor column represented by N levels, and it is given by

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

[20] 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 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 a discussion on the uncertainty in IWV induced by variations in ZPD, P_s, and T_m, see section 2.4.

[21] 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 equation (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 midlatitudes. Since we later intend to use the 40-year reanalyses (ERA40) currently produced at ECMWF at a coarser resolution of about 110 km, the OA data are interpolated accordingly.

[22] The OA data are archived at 6-hour time steps four times per day starting at 0000 UT, whereas ZPD is usually measured instantaneously at 2-hour time steps starting at 0100 UT. In order to obtain ZPD values at the six 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 1200 UT is the average of the measurements at 11 and 1300 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

[23] There are several reasons why the GPS-derived IWV data cannot be compared directly with the IWV data from

the OA. First, they belong to different areas. The GPS measurements are based on samples of the atmosphere forming a cone, where the area on the ground is less than 1 m^2 and increasing with height at a rate determined by the specified elevation cutoff angle. The measured values are representative for some 100 km^2. The OA values are average gridbox values that correspond to an area of about 10,000 km^2. Second, the heights of the GPS stations usually do not agree with the model 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.

[24] The horizontal interpolation of OA model height h to a station coordinate χ_s is done by a weighted linear interpolation from the surrounding four gridboxes with the center coordinates χ_i. For all other OA values, this horizontal interpolation is done using an analytic weighting function $w(\Delta\chi)$ according to *Barnes* [1964]:

$$w(\Delta\chi) = \exp\left(\frac{-\Delta\chi^2}{2D^2}\right), \tag{7}$$

where $\Delta\chi$ is the distance of OA gridbox center to the station coordinate χ_s, and D is a typical length scale of the OA value considered. For IWV and humidity, D is set to 212.5 km, and for surface pressure and temperature, D = 425 km is used (M. Lindskog, Swedish Meteorological and Hydrological Institute, personal communication, 2003). As for model height, only the four gridboxes that surround χ_s are considered in the horizontal interpolation. The horizontal interpolation yields values that represent the OA quantities at the horizontally interpolated OA model surface height.

[25] 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 equation (8):

$$r_j = \frac{p_i q_j}{0.622 e_{S,j}}. \tag{8}$$

[26] The saturated water vapor 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].

$$e_{S,j} = 6.107 \cdot e^{19.83} \cdot \frac{T_j - 273.15}{T_j}. \tag{9}$$

[27] Using equations (8) and (9), the specific humidities $q(h_S)$ at station height and $q(h(\chi_s))$ at model surface height can be obtained from

$$q(h) = \frac{q_1 + q_2}{2} \frac{0.622 e_S(T(h))}{p_s(h)}. \tag{10}$$

[28] 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 (= $\Delta T/\Delta h$) between the two lowest model levels is representative for the atmospheric layer near the surface:

$$\Gamma = \frac{T_2 - T_1}{h_2 - h_1}. \tag{11}$$

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 (even if in some situations a positive lapse rate may be realistic, a test for January/July 2000 has shown that in most of the cases it would introduce errors in the calculated model IWV). 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. This integration is numerically done in 30-m steps, which generally corresponds to a pressure difference smaller than 4 hPa. Here linearity is assumed in the vertical distribution of q between the two height steps:

$$\mathrm{IWV_{OA}} = \mathrm{IWV}(\chi_S) + \sum_{i=1}^{n} \frac{q(h_{i-1}) + q(h_i)}{2}(h_{i-1} - h_i) \tag{12}$$

with

$$h_0 = h(\chi_S),\ h_1 = h(\chi_S) + 30\,\mathrm{m}, \ldots h_n = h_S.$$

2.3. Usage of Surface Pressure

[29] In order to determine IWV with an accuracy of 0.5 mm or less, the surface pressure used in equation (2) requires an accuracy of about 1 hPa or less. Unfortunately, surface pressure measurements are available only at a limited amount of GPS stations (about 40). Thus surface pressure has to be obtained from a different location.

[30] First, it was investigated whether the surface pressure values of the OA (interpolated to the GPS location) can be used instead of surface pressure measurements. In order to assess the accuracy of these OA values, GPS stations were considered where surface pressure was measured simultaneously in the 4 months: January and July of 2000 and 2001. For the majority of the stations the OA surface pressure deviates by more than 3 hPa (for some stations considerably larger) from the observations. For this reason the OA surface pressure cannot directly be used to derive IWV from the ZPD measurements.

[31] Then, it was investigated whether the deviations between the OA pressure values and the observations are constant in time or at least constant within a season. In such a case a constant annual or seasonal OA bias correction could be assigned to each GPS station to estimate the surface pressure at the station from the OA values. However, it was found that the pressure bias did not only depend on the season but also varied between the years with deviations

Table 1. Uncertainty in GPS-Derived IWV Due to Zonal Path Delay Measurements at Locations With Collocated GPS Receivers[a]

			Months Considered			
Stations	Height, m	Variable	January 2000	July 2000	January 2001	July 2001
NRC1/NRC2	131.45	ΔIWV_{bias}	−0.034	−0.367	0.029	0.183
		IWV_{GPS}	4.86	25.60	6.56	24.74
		ΔIWV_r	−0.7%	−1.4%	0.4%	0.7%
NYA1/NYAL	52.01	ΔIWV_{bias}	0.105	−0.829	−0.002	−0.517
	46.27	IWV_{GPS}	4.16	12.13	4.36	12.99
		ΔIWV_r	2.5%	−6.8%	0.0%	−4.0%
TRO1/TROM	107.45	ΔIWV_{bias}	0.407	...	0.614	−0.032
	101.82	IWV_{GPS}	7.47	18.63	7.84	19.23
		ΔIWV_r	5.4%	...	7.8%	−0.2%
YAR1/YAR2	266.83	ΔIWV_{bias}	...	−0.010	...	−0.051
		IWV_{GPS}	27.89	15.41	25.26	14.10
		ΔIWV_r	...	1.9%	...	2.1%

[a] ΔIWV_{bias} is the mean difference in daily IWV bias between the two stations (first and second) in millimeters. IWV_{GPS} is the mean daily GPS-derived IWV of the two stations in millimeters. ΔIWV_r is fraction ΔIWV_{bias} divided by IWV_{GPS} in percent.

larger than 1 hPa. For this reason, the assignment of a fixed model pressure bias correction to each station was ruled out.

[32] Instead, we decided to use surface pressure from synoptic stations of the World Meteorological Organization's (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.

[33] 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 4 months considered in the present study, GPS measurements and nearby pressure observations are available for about 120 stations of the IGS global network.

[34] 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 the bulk temperature are available at a 6-hour time step, equation (13) is used for the computation of $p_s(h_S)$, which is derived from the barometric height formula.

$$p_s(h_S) = p_s(h_{WMO}) e^{g\frac{h_{WMO}-h_S}{R_L T_v}}. \qquad (13)$$

[35] If only the mean sea level pressure p_0 and the bulk temperature are available, the barometric height formula is used directly (equation (14)) to compute $p_s(h_S)$:

$$p_s(h_S) = p_0\, e^{-g\frac{h_S}{R_L T_v}}. \qquad (14)$$

[36] Both equations (13) and (14) are stepwise computed over 20-m height steps by assuming that the bulk temperatures follow the wet adiabatic lapse rate of −0.65 K/100 m. If only surface pressure $p_s(h_{WMO})$ and mean sea level pressure p_0 are available, equation (15) is used for the computation of $p_s(h_S)$, which is derived from equation (14) by assuming that the fraction between the two bulk temperatures at GPS height and WMO height is close to one.

$$p_s(h_S) = p_0\left(\frac{p_s(h_{WMO})}{p_0}\right)^{h_s/h_{WMO}}. \qquad (15)$$

2.4. Uncertainty of GPS-Derived IWV

[37] 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 water vapor column taken from the OA is found to be rather small.

[38] 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.

[39] An indication of the actual uncertainty induced by the ZPD measurements is given in Table 1 Here colocated 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 colocated stations directly as the days with ZPD measurements mostly do not agree for these stations in the 4 months considered. This means that in these 4 months, continuous measurements are not available for the colocated GPS stations, and the number of days with simultaneous measurements at both stations is too small to yield accurate uncertainty estimates. Therefore the IWV biases are compared.

[40] Uncertainty related to the use of the WMO surface pressure measurements is given in Table 2. Here a few randomly selected stations are listed where two (three for UPAD) WMO stations exist at similar distances close to the

Table 2. Uncertainty in GPS-Derived IWV Due to Surface Pressure Measurements (Using Different WMO Stations to Get the Pressure)[a]

		Distance to GPS Station			Months Considered			
Stations		Height, m	Horizontal, km	Variable	January 2000	July 2000	January 2001	July 2001
ALBH	1	−7.1	29.2	$\Delta\mathrm{IWV}_{\mathrm{bias}}$	...	...	0.110	−0.397
	2	−4.1	31.7	$\mathrm{IWV}_{\mathrm{GPS}}$	...	...	11.40	20.17
				$\Delta\mathrm{IWV}_r$	...	...	1.0%	−2.0%
BAKO	1	−97	36.1	$\Delta\mathrm{IWV}_{\mathrm{bias}}$	−0.438	−2.046	−0.379	−2.468
	2	−135	34.3	$\mathrm{IWV}_{\mathrm{GPS}}$	56.91	44.32	57.33	41.21
				$\Delta\mathrm{IWV}_r$	−0.8%	−4.6%	−0.7%	−6.0%
GRAZ	1	+42.9	6.8	$\Delta\mathrm{IWV}_{\mathrm{bias}}$	...	...	−0.188	−0.076
	2	−143.1	8.7	$\mathrm{IWV}_{\mathrm{GPS}}$	...	...	10.04	25.65
				$\Delta\mathrm{IWV}_r$	...	...	−1.9%	−0.3%
KIRU	1	−1.1	79.7	$\Delta\mathrm{IWV}_{\mathrm{bias}}$	0.161	−0.101	0.213	0.101
	2	+106.9	81.1	$\mathrm{IWV}_{\mathrm{GPS}}$	4.90	18.74	6.07	18.01
				$\Delta\mathrm{IWV}_r$	3.3%	−0.5%	3.5%	0.6%
LAMA	1	−22.2	21.7	$\Delta\mathrm{IWV}_{\mathrm{bias}}$	0.461	0.317	0.050	0.242
	2	−49.2	49.6	$\mathrm{IWV}_{\mathrm{GPS}}$	8.81	23.98	9.12	30.66
				$\Delta\mathrm{IWV}_r$	5.2%	1.3%	0.5%	0.8%
TRO1	1	−97.5	2.4	$\Delta\mathrm{IWV}_{\mathrm{bias}}$	−0.047	0.082	0.118	...
	2	+2.6	1.5	$\mathrm{IWV}_{\mathrm{GPS}}$	6.75	18.63	7.51	19.23
				$\Delta\mathrm{IWV}_r$	−0.7%	0.4%	1.6%	...
UPAD	1	6.4	35.3	$\Delta\mathrm{IWV}_{\mathrm{bias}}$	0.391	0.457	0.362	0.445
					−0.118	0.029	0.133	0.142
					−0.510	−0.429	−0.229	−0.304
	2	13.4	33.3	$\mathrm{IWV}_{\mathrm{GPS}}$	7.96	26.42	14.00	31.85
					7.76	26.51	13.92	31.74
					7.98	26.26	13.92	31.92
	3	−33.6	37.0	$\Delta\mathrm{IWV}_r$	4.9%	1.7%	2.6%	1.4%
					−1.5%	0.1%	1.0%	0.4%
					−6.4%	−1.6%	−1.6%	−1.0%

[a] $\Delta\mathrm{IWV}_{\mathrm{bias}}$ is the mean difference in daily IWV bias between the two stations (first and second) in millimeters. For UPAD, the differences are first to second, first to third, and second to third, respectively. $\mathrm{IWV}_{\mathrm{GPS}}$ is the mean daily GPS-derived IWV of the two stations in millimeters. $\Delta\mathrm{IWV}_r$ is fraction $\Delta\mathrm{IWV}_{\mathrm{bias}}$ divided by $\mathrm{IWV}_{\mathrm{GPS}}$ in percent.

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. For BAKO, the large values in the difference of the IWV biases in July are related to the fact that at the station location (Indonesia) the OA seems to have problems with several weather situations in both July months. The first WMO station has measured the pressure for almost all days in the 2 months; the second station has measured values only for half of the days within the month. In both months the weather situations occurring on these days are captured comparatively well by the OA so that the daily IWV bias is small. However, for the second station which covers the whole month the calculated daily IWV bias is much larger as here all weather situations are included.

[41] For the four GPS stations BAHR, MATE, POTS, and USNO, where surface pressure measurements are available at the station, we compared the monthly mean pressure with surrounding WMO stations (two for MATE and three otherwise). The mean bias introduced by the use of these stations is 0.85 hPa. If only the closest WMO stations are used the mean bias is 0.87 hPa. This suggests that uncertainties introduced by the use of nearby pressure measurements are mainly influenced by measurement uncertainties and pressure interpolation to the GPS station height and only to a less extent by the horizontal distance between the WMO station and the GPS station. An uncertainty of less than 1 hPa corresponds to an uncertainty of less than 0.4 mm in IWV, which agrees well with the results for the randomly selected GPS stations listed in Table 2.

[42] The values obtained from Tables 1 and 2 agree quite well with the known quality of GPS-derived IWV [*Bengtsson et al.*, 2003a], which have biases and standard deviations in comparisons to collocated instruments like water vapor radiometers or radiosondes, as well as to numerical weather models in the range of 0.5–1.5 mm IWV. The expected quality is generally higher in midlatitudes and lower in the ionospheric active regions near the equator.

[43] For stations where there are large height differences between the GPS station and the WMO pressure measurements the vertical pressure interpolation may not be fully valid so that 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) stations. This introduces on several occasions errors in the GPS-derived IWV, causing negative values in July 2000 and 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

[44] 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

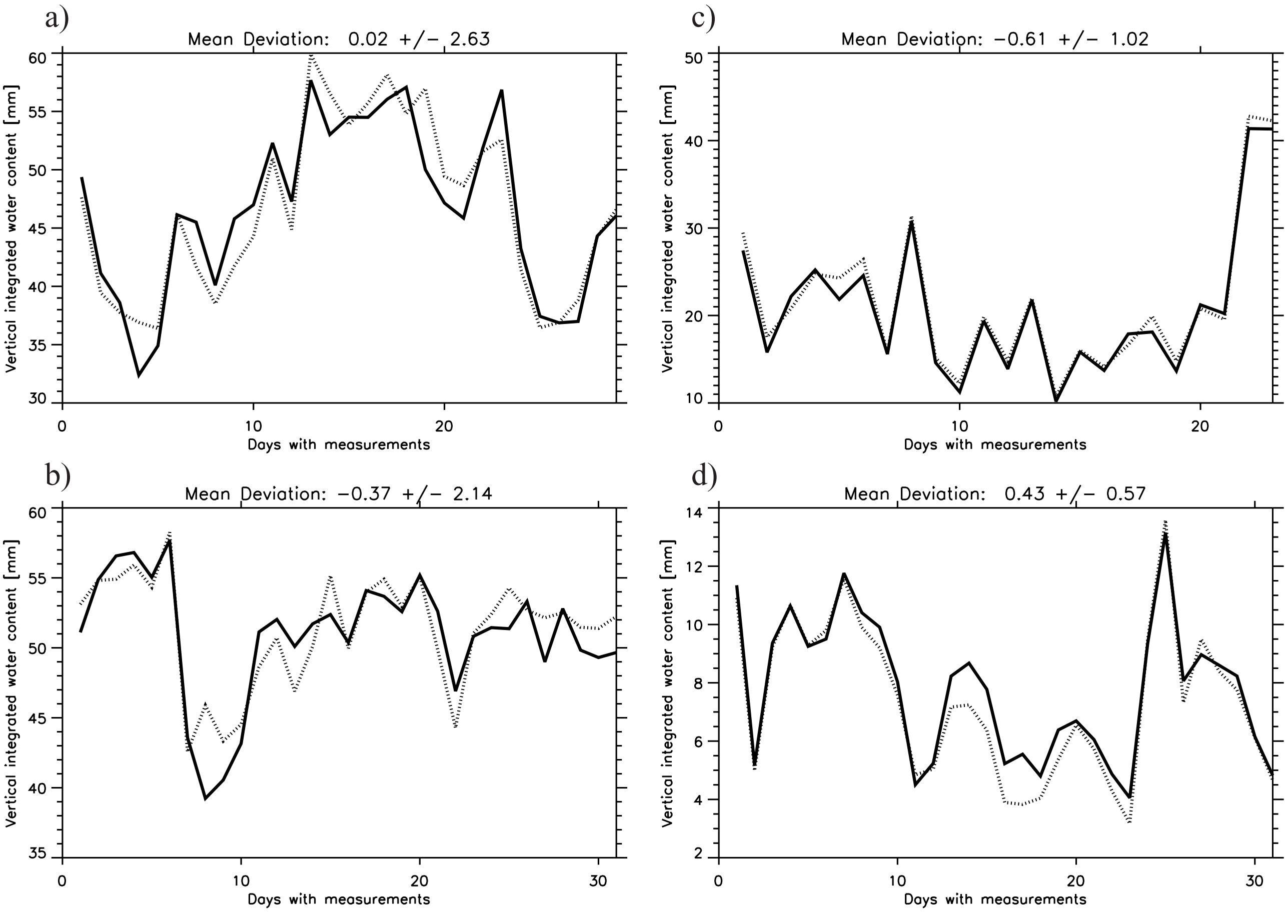

Figure 2. GPS-derived (dotted) and OA (solid) IWV for July 2000 at station (a) DGAR (Indian Ocean), (b) GUAM (West Pacific), and for January 2001 at station (c) GOUG (South Atlantic) and (d) METS (Finland).

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 analyzed data. The model data are also limited by the numerical resolution of the model and the way orographical obstacles and coastlines are resolved by the model. However, the intercomparison is restricted to the integrated water vapor 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 vapor to be consistent with the GPS-derived IWV. As we will see below this is also the case.

[45] 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 analyzed and observed IWV in a comprehensive way. If both data sets agree such that both the standard deviation of daily differences as well as the monthly averaged difference (bias) are small we may conclude that both the GPS-derived values and analyzed fields are correct, in particular if this is the case for all the 4 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 IWVs seldom are equally erroneous in every weather situation. Finally, in the case when the bias is small and the SD is large we may assume that the analyzed data are likely to be in error since the quality of the GPS measurements is not likely to show large variations with time, while the quality of the analyzed IWV depends on the weather situation.

[46] 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. However, 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

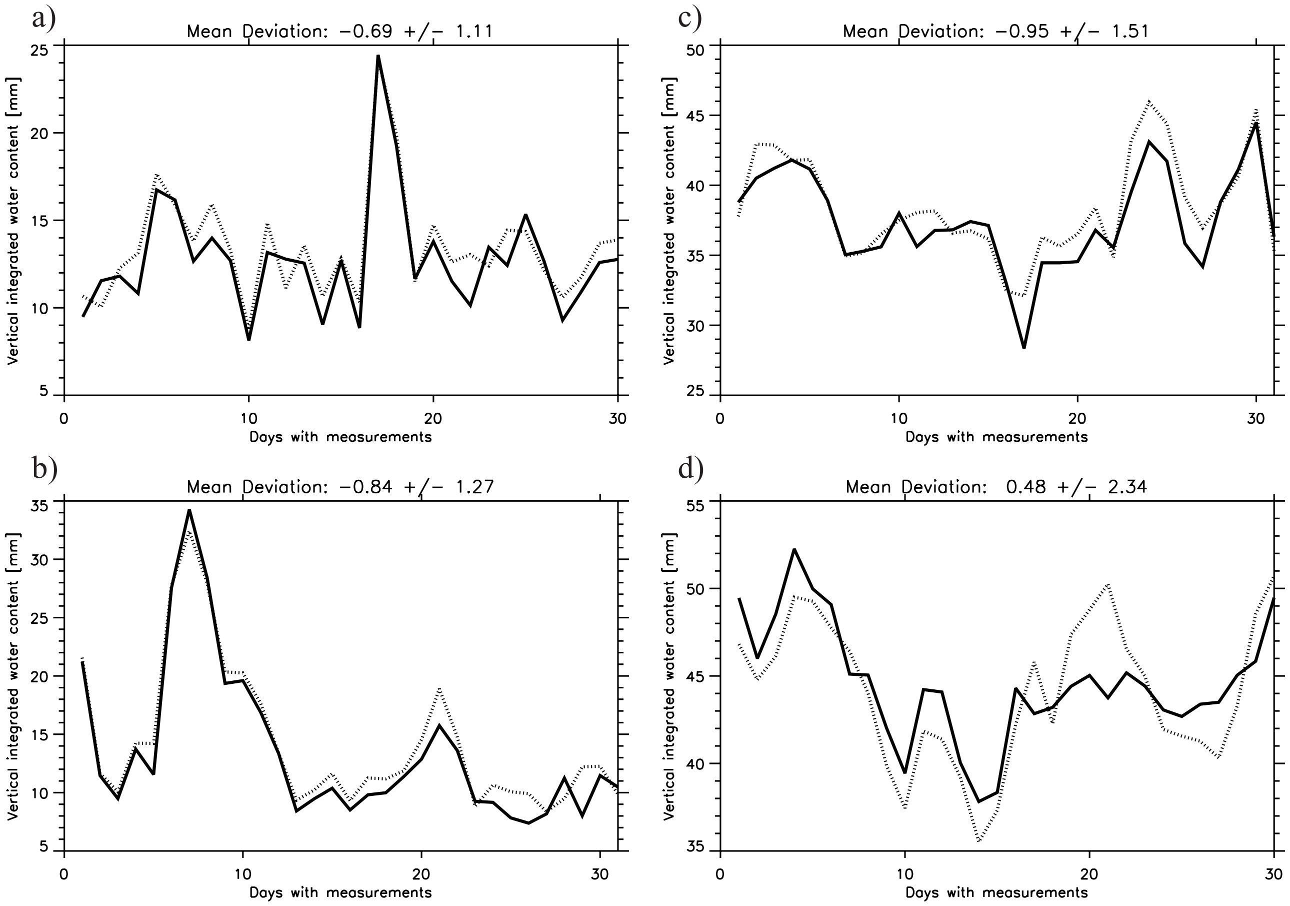

Figure 3. GPS-derived (dotted) and OA (solid) IWV for July 2000 at station (a) CEDU (South Australia), (b) LPGS (Argentina), (c) MALI (Kenya), and (d) NKLG (Gabon).

blacklisted and not used for the validation of the OA IWV in section 3.1.

3.1. Validation of OA IWV Distribution

[47] In general, the OA IWV agrees well with the GPS-derived values, and both bias and SD are small (Figures 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.

[48] 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 United States/Canada and Siberia clearly shows up,

Table 3. Regional Station Averages of Fractional Bias (ΔIWV_{bias} Divided by IWV_{GPS}) in Percent

			January 2000/2001		July 2000/2001	
Region	Latitude	Longitude	N_{Stat}	Bias, %	N_{Stat}	Bias, %
North America	30°N–90°N	170°W–50°W	24	−6.73	22	−2.54
Central United States/Canada	35°N–65°N	120°W–70°W	12	−15.58	12	−2.56
Central America	5°N–30°N	115°W–55°W	4	−1.32	4	−1.74
South America	55°S–10°N	85°W–30°W	3	−2.38	3	−3.21
Southern Africa	40°S–5°N	5°E–55°E	3	0.47	3	−0.44
Europe	35°N–75°N	15°W–45°E	35	0.44	36	−0.41
Baltic Sea catchment	50°N–70°N	5°E–40°E	15	−1.42	15	−0.75
Central Europe	42°N–55°N	5°E–30°E	16	1.37	17	0.64
Mediterranean Sea	30°N–45°N	10°W–40°E	14	−2.12	16	1.32
Siberia	50°N–80°N	60°E–180°E	7	−19.22	9	−1.07
Saudi Arabia	10°N–35°N	30°E–60°E	4	−2.30	5	3.23
Southern Asia	0°N–35°N	60°E–150°E	5	2.68	4	0.27
Tropical Indian/Pacific Ocean	15°S–15°N	60°E–180°E	8	−2.36	7	−1.33
Australia	45°S–10°S	110°E–150°E	7	−2.36	8	−1.89
Australia and surroundings	60°S–0°S	90°E–180°E	12	−3.81	12	−2.64

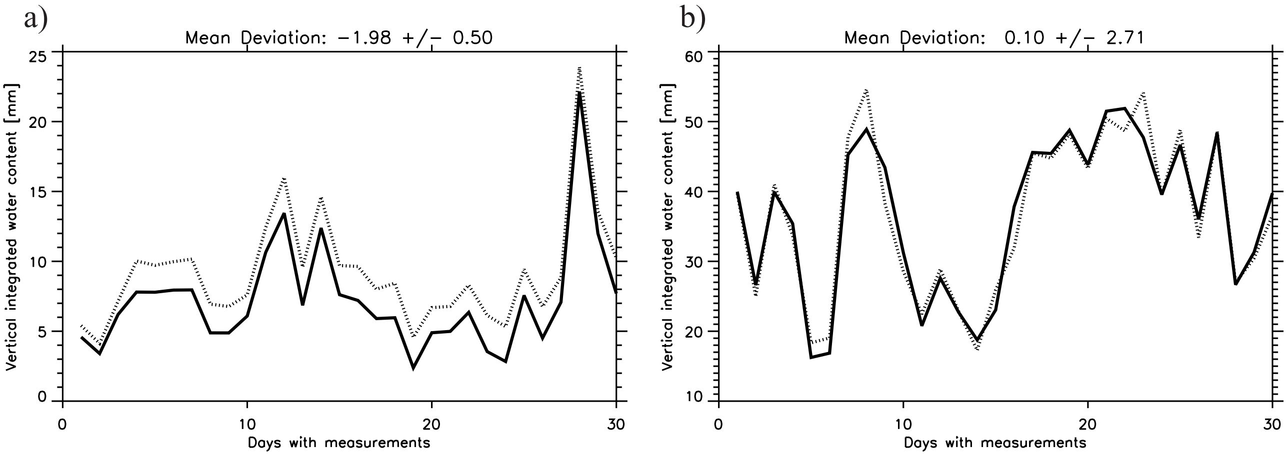

Figure 4. GPS-derived (dotted) and OA (solid) IWV at station NLIB (Iowa) for (a) January 2001 and (b) July 2001.

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. 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 (10 in January, 9 in July).

[49] In order to analyze 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.

[50] 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 four times larger than the SD. However, 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 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 independent 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].

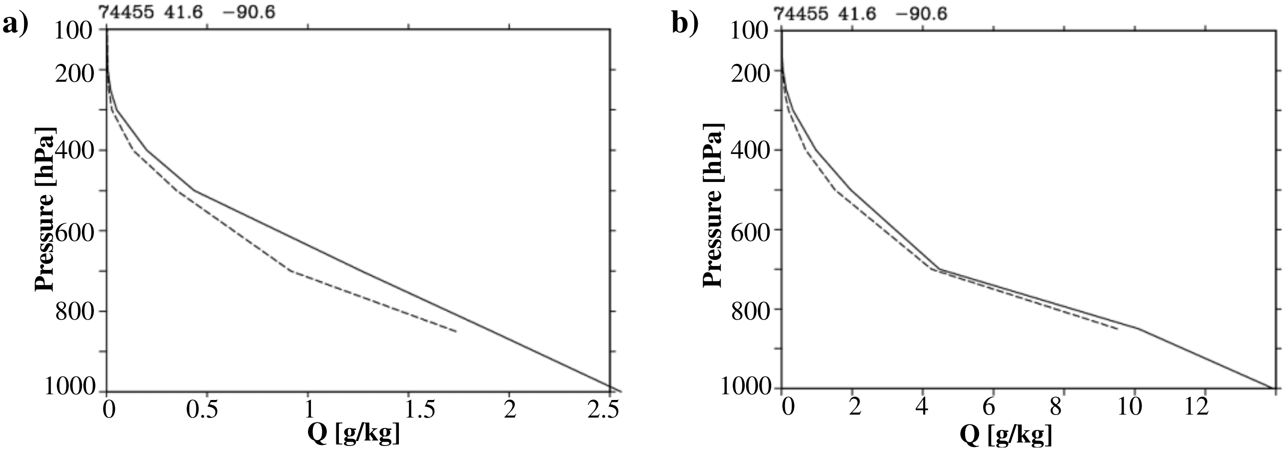

Figure 5. Vertical humidity profiles from radiosonde measurements (dashed) and OA (solid) at the Quad City station (WMO 74455) in Iowa for (a) January 2001 and (b) July 2001.

Table 4. Selected Suspicious Stations, Mostly With a Daily IWV Bias Larger Than Its Standard Deviation (SD)[a]

Station	Location	Bias, SD	Height Above Sea Level, m			Horizontal Distance p_S-GPS, km
			p_S	GPS	OA	
ASC1	tropical Atlantic	+1.2	79	92	1	2.3
CAS1	Antarctica	−3.4	42	37	342	0.6
DAV1	Antarctica	−3.9	22	27	457	0.8
EISL	South Pacific	−1.2	51	153	1	5.4
HFLK	Innsbruck	+1.1	2336/593	2336	1176	0./5.8
HOFN	Iceland	−2.6	21	50	430	3.8
KABR	Israel	−0.5	8	84	332	26.9
KELY	Greenland	−4.2	53	227	621	11.2
KODK	Alaska	−2.6	6	21	112	0.2
KOKB	Hawaii	+1.9	1147	1147	11	0.0
LHAS	Himalaya	−0.8	3661	3661	4851	0.0
MAW1	Antarctica	−1.7	16	32	585	0.6
NPLD	London	−9.6	31	402	9	23.7
PERT	SW Australia	+0.9	20	45	182	16.5
THTI	South Pacific	+1.4	2	38	9	3.2
THU1	Greenland	−3.7	62	57	305	1.1

[a] 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 neighboring synoptic station in the other 3 months.

[51] 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.*, 2003b] for January 2001 may help to clarify this question.

3.2. Identification of Erroneous Measurements

[52] 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].

[53] 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

[54] 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 three of the 4 months. These stations are investigated in more detail in the following.

[55] 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) 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

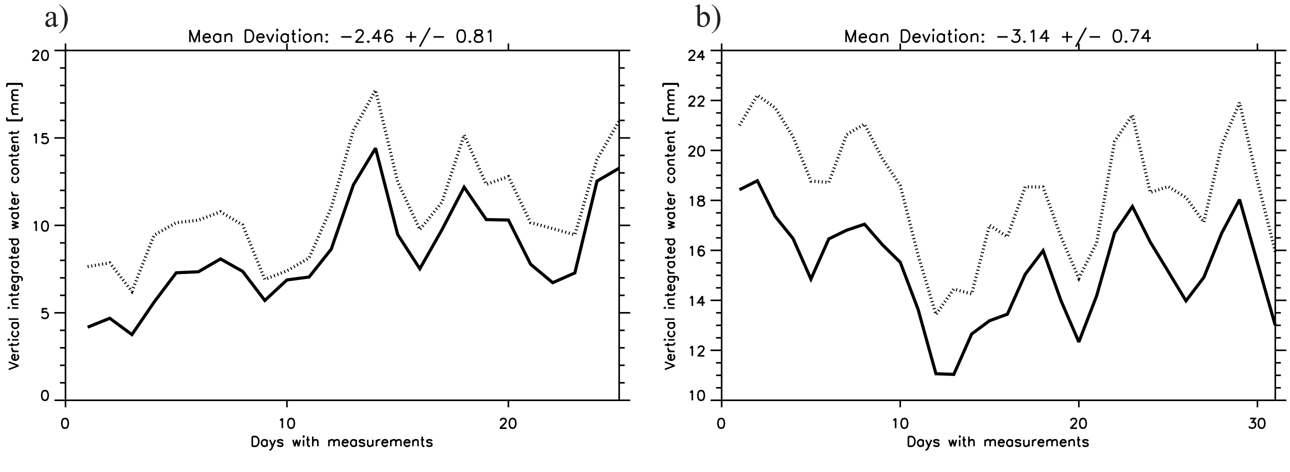

Figure 6. GPS-derived (dotted) and OA (solid) IWV at station HOFN (Iceland) for (a) January 2001 and (b) July 2001.

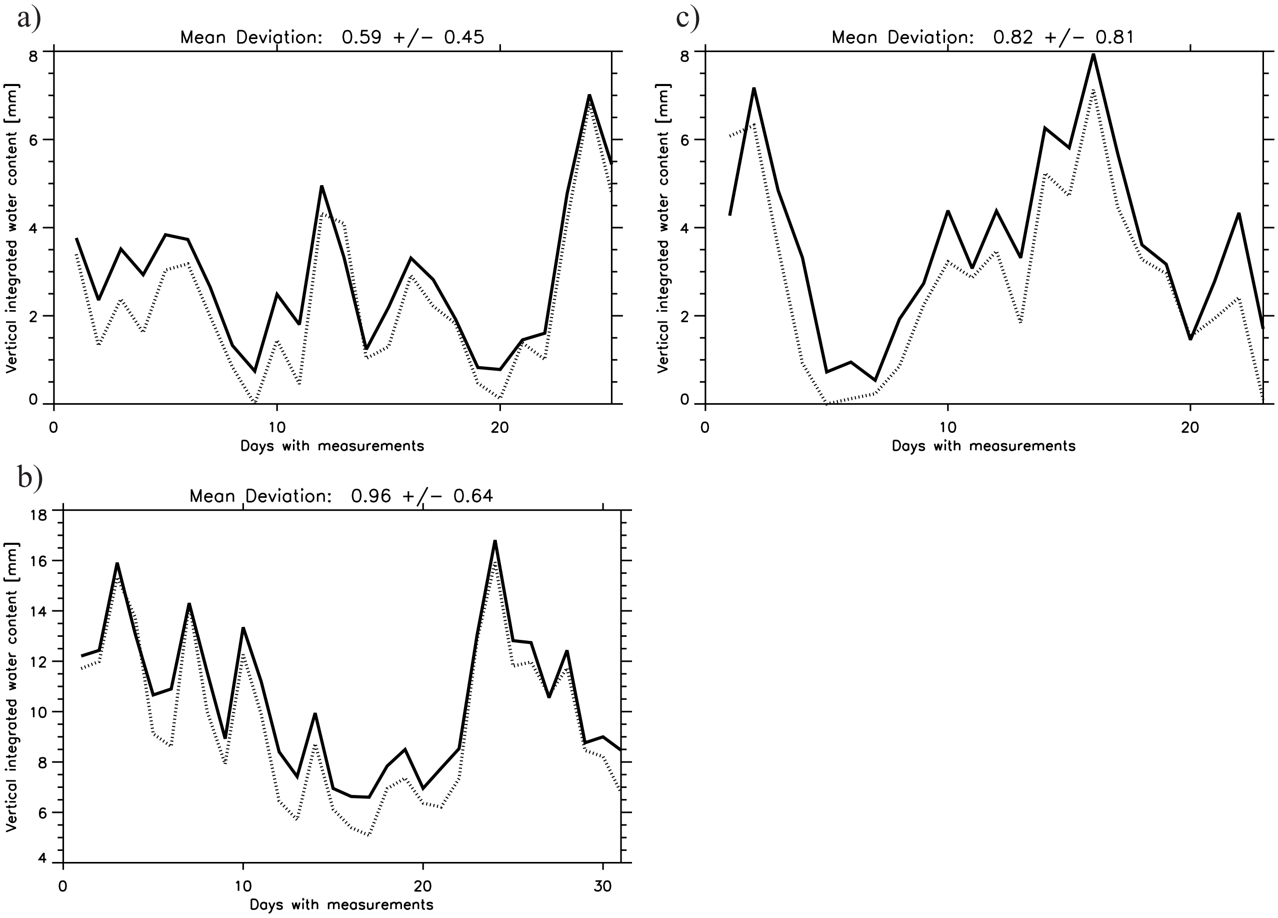

Figure 7. GPS-derived (dotted) and OA (solid) IWV at station HFLK (Austria) with RINEX pressure for (a) January 2000 and with WMO pressure for (b) July 2000 and (c) January 2001.

topography gradients should be less pronounced so that it may well be that the OA model does not capture everything in this region.

[56] 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 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

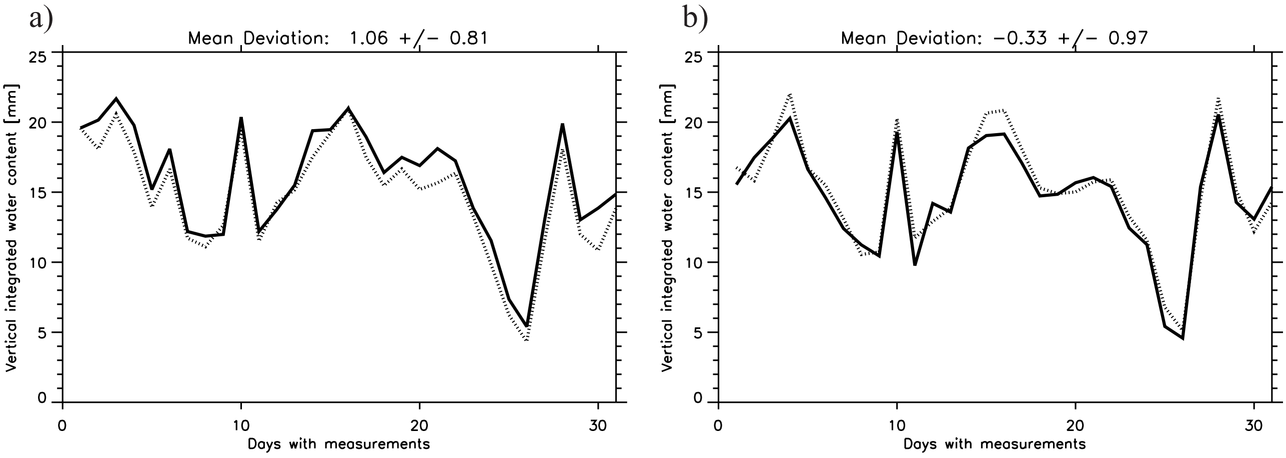

Figure 8. GPS-derived (dotted) and OA (solid) IWV for July 2000 at the SW Australian stations: (a) PERT and (b) YAR1.

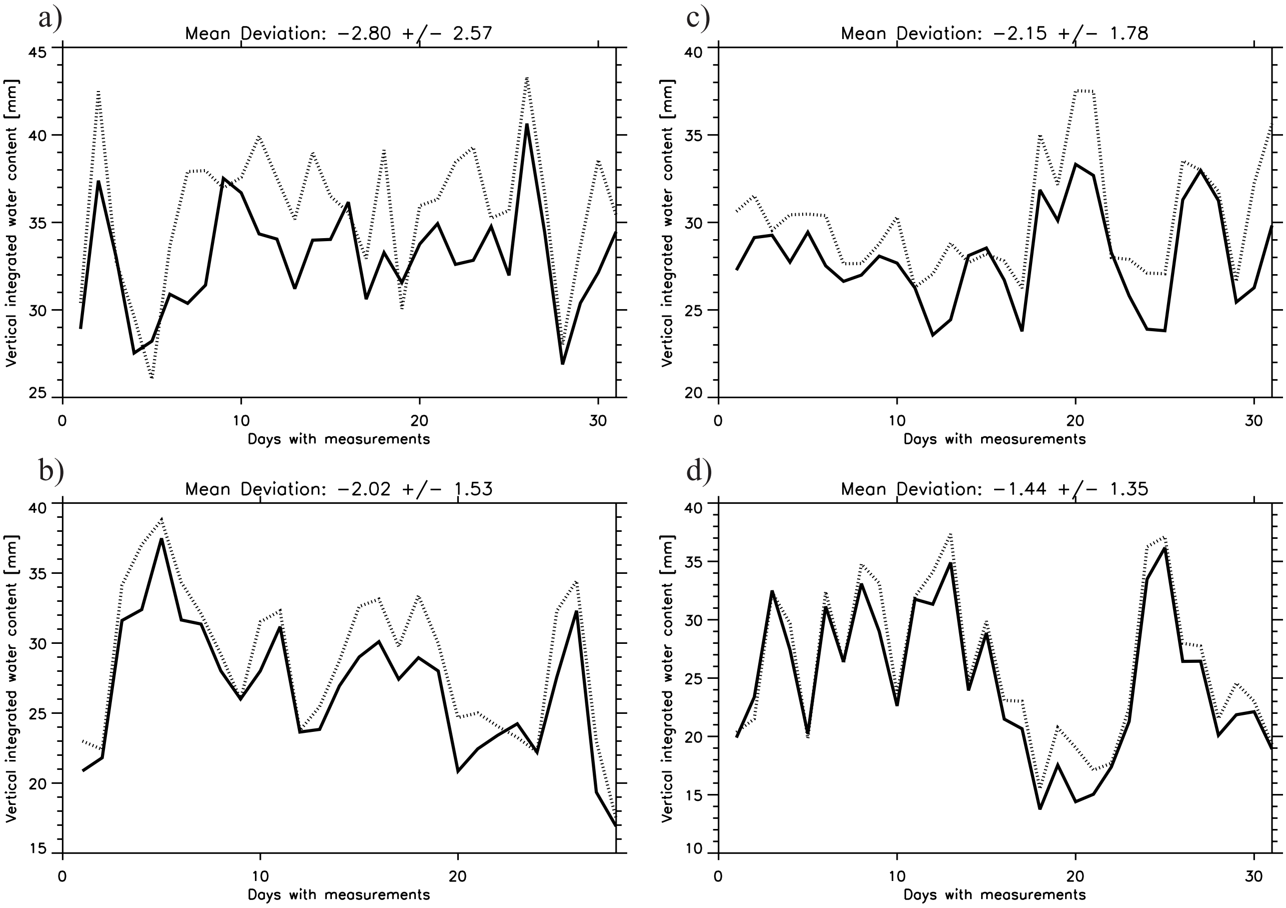

Figure 9. GPS-derived (dotted) and OA (solid) IWV at station EISL (Easter Island) for (a) January 2000, (b) July 2000, (c) January 2001, and (d) July 2001.

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 (Figures 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.

[57] The third group concerns stations where the station height is very high so that the assumption of homogeneity in the boundary layer does not 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) even though the IWV bias is smaller than the SD in the 2 months (January/July 2001) when data are available at the LHAS station. Other GPS stations at similar heights were excluded from the present study beforehand.

[58] The fourth group concerns stations which have systematic errors in the measured data itself. This seems to be the case for NPLD, KODK, KABR, and PERT. 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), KABR (Israel), 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 neighboring 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. Similarly, KABR was identified as a suspicious station by comparing the IWV biases at the station to the biases at other GPS stations in the close vicinity. Here it is assumed that the quality of the OA IWV does not change significantly. The biases obtained at KABR are inconsistent to the biases at the surrounding stations BSHM (for which the same WMO pressure measurement are used), DRAG, and GILB.

[59] 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 (Figures 10a and 10b, tropical Atlantic, position of the inner Tropical Convergence Zone) and THTI (Figures 10c and 10d, tropical Pacific, position of the SPCZ).

[60] Except for ASC1, EISL, HFLK, and THTI, all stations included in Table 4 are afflicted with systematic

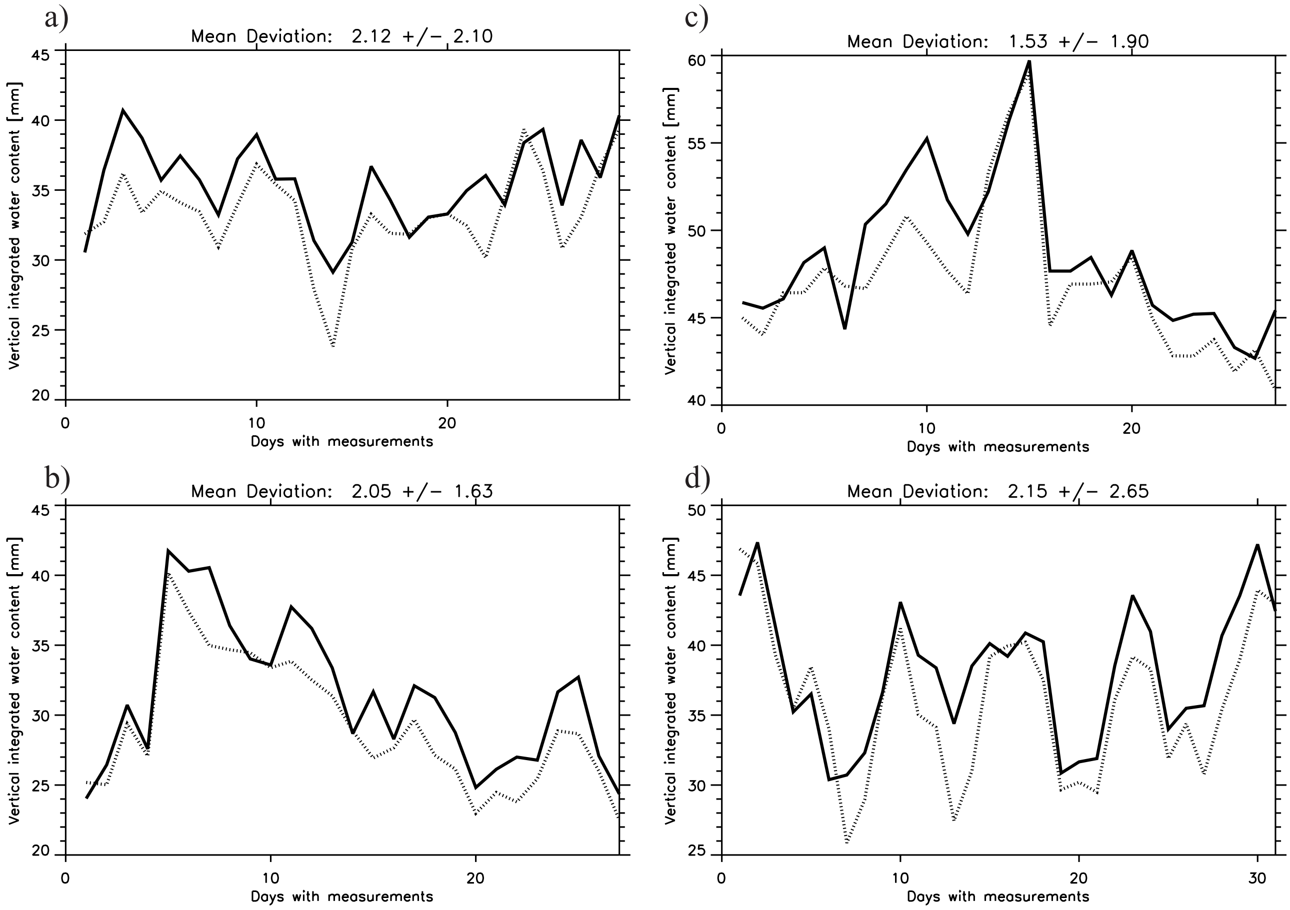

Figure 10. GPS-derived (dotted) and OA (solid) IWV at station ASC1 (Tropical Atlantic) for (a) January 2000, (b) July 2000, and at station THTI (Tahiti) for (c) January 2000 and (d) July 2000.

errors so that they must be blacklisted in model validation studies, as it was done in section 3.1. For studies of long-term changes in the IWV itself these stations can still be used.

4. Conclusions and Future Works

[61] 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 ($\leq$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 behavior is generally the same for both summer and winter months except for winter data in the interior of the United States and Eurasia, where the modeled 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 midlatitudinal dry regions is a subject for future studies.

[62] Although the main objective is to assess the usefulness of global GPS measurements for climate monitoring and model validation, it is important to highlight that also the analyzed fields can be used to identify errors in the GPS-derived data and to identify areas where the GPS data are less relevant to use. We have found several examples where the GPS-derived data have systematic errors. This approach is analogous to the methods applied in operational numerical weather prediction [e.g., *Hollingsworth et al.*, 1986]. The second is to identify areas where the numerical model has insufficient resolution to describe the water vapor profile due to sharp climate and weather boundaries. Typical cases are stations located at steep mountain slopes, e.g., the station HOFN near Mount Vatnajökull on Iceland (see section 3.3), or near major land ice areas such as Greenland or Antarctica. So in order to arrive at a representative sample of GPS station such errors or anomalies need to be identified. Using the 4 months considered in this study, it was possible to identify problematic stations that must be blacklisted in model validation studies at resolutions comparable to T106 or coarser (cf. Table 4). Consequently, these stations were excluded from the validation of the OA IWV described above. For studies of long-term changes in the IWV itself these stations can still be used.

[63] For some of the problematic stations, but also in 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 if the resulting uncertainty in interpolated pressure values, based on the existing observational network, is larger than 0.5 hPa. Only if the accuracy of the pressure values is on the order of 0.5 hPa or less the GPS data can be useful for monitoring and model validation. For the accuracy required, the pressure instruments can be rather inexpensive devices.

[64] On the basis of 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 vapor. Because of external variations on interannual timescales mainly related to El Niño-Southern Oscillation (ENSO) events, such a network should be established for long-term operation. A first study to investigate long-term changes in IWV was made by *Gradinarsky et al.* [2002], who found a general increase in IWV over Scandinavia for a 6-year period starting in 1995 (although with large variations over the area). 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. Needless to say that the GPS data are also very useful to check the high-frequency component of water vapor (such as the diurnal cycle), although this was not the main objective of this study.

[65] The GPS-derived IWV values will further be used to validate the most recent years of the new 40 years reanalyses that is currently produced at ECMWF. Such work is in progress and will also be carried out along the lines used by *Bengtsson et al.* [2003b].

[66] **Acknowledgments.** We thank Norbert Kreitz from the European Centre of Medium-Range Weather Forecasts, who has provided us with technical support in accessing the WMO pressure data. We are grateful to Klaus Arpe for fruitful discussions about our results and for plotting the humidity profiles. This study was supported by funding from the European Union within the ERA40 project (contract EVK2-CT-1999-00027 ERA-40).

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