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Estimation of precipitable water vapour from GPS measurements in Argentina: Validation and qualitative analysis of results

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Abstract

This paper presents PWV estimates from GPS data computed at four continuously operated GPS stations in Argentina established at Buenos Aires, Córdoba, Rosario and Salta over a 1 year period (2006–2007). The objective is to analyze the behaviour of the GPS PWV estimation using mean tropospheric temperature (T_m) values from the Bevis model, Sapucci model and obtained by a numerical integration of variables provided by the operational analysis of the National Centre of Environmental Prediction (NCEP). The results are validated using PWV values from nearest radio soundings. Moreover, a comparison between PWV values determined from microwave sensors deployed on the NOAA-18 satellite and PWV from GPS observations is also presented.

From the analysis we can see that the computation of GPS PWV using the T_m from the Bevis model, originally deduced for the northern hemisphere, shows similar behaviour to the respective computation using a Sapucci model inside 0.5 mm. The differences between the T_m values computed from the Sapucci model and the numerical integration of NCEP variables are of the order of 15 K, although it does not represent a significant error in PWV.

Nevertheless, differences in bias are imperceptible during the dry period and they are as big as 3 mm during the moist or high precipitation period. This behaviour could not represent an improvement when comparing radio soundings with respect to the GPS PWV values using different estimations of T_m. Thus, we conclude that the usage of T_m estimated from the Bevis model is the best choice for regional studies, considering the simplicity and dissemination of the method, unless some more studies taking into account the geographical and climatological characteristic of the region are performed. As expected, GPS PWV values show very good agreement with radio sounding determinations, small differences can be observed especially during extreme precipitation periods. In general the NOAA PWV values denote an over estimation of the available water vapour. It is important to note that the determination of PWV is not the mean product of the NOAA-18 satellite mission. These results show the potential of such a product although a preliminary calibration using GPS PWV is still necessary.

Keywords: Global Positioning System; Precipitable water vapour; Mean tropospheric temperature

1. Introduction

Water vapour is one of the meteorological variables that presents major difficulties in its measurement. Although radio soundings show the vertical profile of the quantity of water vapour present in the atmosphere, due to their high cost, operational networks provide neither high spa-

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tial nor high temporal resolution. On the other hand, observations from remote sensors, such as radars or satellites, still present important differences from observed parameters. The importance of suitable values of water vapour resides in the utilization of the same values for forecasting of precipitation and of all meteorological phenomena associated with it, with temporal scales from hours to seasonal forecasts. Obtaining integrated water vapour along a vertical profile using geodetic information from GPS (Global Positioning System) stations has been developed in numerous places around the world, with important meteorological applications.

Mendes et al. (2000) evaluated T_m from the following models: Bevis et al. (1992); two expressions from Mendes (1999); and four models derived from Emardson and Derks (2000). They conclude there is little gain in using regionally adapted models. Schueler et al. (2001) proposed three different numerical expressions for T_m, taking into account its variation in latitude and seasonal effects. These expressions depend on site-specific coefficients given for 335 GPS sites. Jade et al. (2005) presented GPS PWV values for four continuously operated stations in India. They also evaluated seven different models to estimate T_m and they found no differences in the resultant PWV. Deblonde et al. (2005) evaluated GPS PWV from two different datasets: 22 GPS receivers in Canada for 4 months and 112 sites from the International GNSS Service global network for 7 months. They compared GPS PWV with 6 h PWV forecasts from a global multi-scale model and radio sounding (RS PWV) values. Results were found to be in close agreement, especially in the cold and relatively dry conditions (mean PWV near 15 mm) of the Canadian climate.

Snajdrova et al. (2006) compared Very Large Baseline Interferometry (VLBI) PWV values from 15 continuous days of VLBI observations with other co-located space geodetic techniques and also with Water Vapour Radiometer (WVR) measurements where available. In particular, the comparison between VLBI and GPS PWV showed good agreement at the 3–7 mm level.

Saha et al. (2007) analyzed the GPS tropospheric range errors for 3 years at eight stations in different geographical and climatic areas over India. They proposed different empirical site-specific models for the tropospheric zenith dry delay as well as the tropospheric zenith wet delay. Nevertheless, they recommended the usage of a unified linear model for zenith dry delay in terms of surface pressure and a second order unified model for zenith wet delay in terms of water vapour partial pressure.

Jade and Vijayan (2008) estimated GPS PWV at 28 GPS stations in India over a 4 year period. They used a vertical interpolation of grid data from the National Centre of Environmental Prediction (NCEP) instead of the operationally measured meteorological data. They compared the computed GPS PWV values with PWV from nearby radio sonde sites and GPS PWV with interpolated values from grid NCEP water vapour data. They found that the GPS water vapour values are comparable to the accuracy of RS PWV determinations. Besides, GPS PWV proved to be helpful when investigating local climatological events like monsoon circulation.

Jin et al. (2009) studied 5 years of VLBI and GPS PWV time series at 14 co-located sites with radio sondes available. They found that the monthly averaged GPS PWV values are close to radio sonde measurements at 1 mm, however VLBI determinations are systematically smaller than GPS estimates for all sites by as much as 15–30%. Jin and Luo (2009) analyzed 13 years at 2 h resolution of GPS PWV values from 155 global sites in order to investigate multi-scale water vapour variability. They clearly detected seasonal variations as well as significant diurnal and weaker semidiurnal variations.

Previous studies in South America like those of Sapucci et al. (2004) proved the importance of this information for Brazil and developed new skills for a more effective calculation of this variable by obtaining better regional parameters. On the other hand, Falvey and Garreaud (2005) showed the efficiency of this tool for meteorological or climatic studies. They observed the seasonal variability of the availability of water vapour on The Altiplano (plateau over The Andes region located on the border of Bolivia and Peru) and its relation with wind fields.

The present paper has two main objectives. Firstly, this work finds a suitable estimation of integrated precipitable water vapour (PWV) along the zenith direction of the observer from GPS for the central and northern region of Argentina. The second objective centres on a validation of this information and compares it with other available estimations. In order to reach the first objective, we compare and analyze the PWV obtained through geodetic quality processing of GPS measurements from four permanent GPS stations operating in Argentina (Fig. 1): Buenos Aires (IGM1), Córdoba (UCOR), Salta (UNSA) and Rosario (UNRO) (see Table 1) over a 1 year period. The behaviour of the different GPS PWV time series obtained from different estimations of the mean tropospheric temperature (T_m)

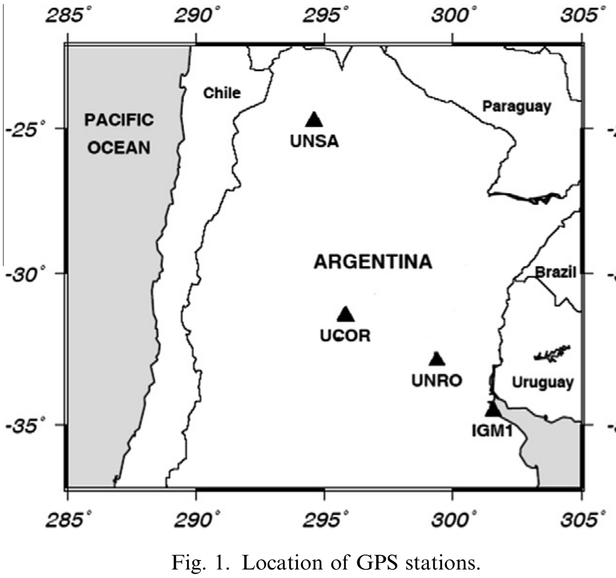

Fig. 1. Location of GPS stations.

Table 1
Location of GPS stations in geodetic coordinates ITRF2000.

Station	Latitude (° ′ ″)	Longitude (° ′ ″)	Height (m)
IGM1	−34 34 20.08	−58 26 21.55	50.7539
UCOR	−31 26 05.86	−64 11 36.62	462.8308
UNSA	−24 43 38.84	−65 24 27.52	1257.791
UNRO	−32 57 33.67	−60 37 42.33	66.92

is analyzed. In particular, T_m is computed using the well-known model of Bevis (Bevis et al., 1992), which is usually applied in the northern hemisphere. T_m is also computed using the empirical model of Sapucci (Sapucci et al., 2004). The latter model divides Brazil into five climatic regions taking into account their geographical and seasonal characteristics. We extrapolate the empirical equation adopted for the southern part of Brazil.

Moreover the GPS PWV values are also estimated from T_m calculated by numerical integration of variables provided by the operational analysis of the NCEP. The second objective is achieved by making a comparison between GPS PWV with regard to PWV values obtained from radio soundings near the GPS stations. The different time series are compared and their correlations are shown. Besides, PWV values are computed from microwave observations of the NOAA-18 satellite (NOAA PWV). The quality of this estimation is statistically tested with regard to GPS PWV values.

2. Data analysis

2.1. Data description

In this study, we consider a geodetic network of 59 stations distributed over several countries of South America. Such points are continuously operating GPS stations that contribute to the SIRGAS (Sistema de Referencia Geocéntrico para las Américas) network (http://www.sirgas.org). The GPS observation data sets in RINEX format, as well as the final combination of orbits, phase centre variations and Earth rotation parameters are from the International GNSS Service (IGS, ftp://cddisa.gsfc.nasa.gov/).

The Argentinean National Weather Service (SMN, Servicio Meteorológico Nacional) provides not only surface meteorological parameters, but is also responsible for the radio soundings launched at their operating stations every day at 12 UTC.

In particular, we used the only three radio sounding stations available during the chosen period close to the selected GPS stations: Córdoba (SACO) near the UCOR station, Ezeiza (SAEZ) in Buenos Aires, close to the IGM1 station and Salta (SASA) near the UNSA station. Information on every station is shown in Table 1 for GPS and Table 2 for radio soundings. It is important to note that the GPS height refers to the GRS80 ellipsoid, while the RS station height refers to mean sea level. Table 2 also shows the orthometric height differences of the RS stations with respect to the GPS sites. Note that there are no values of radio sounding available from the GPS station UNRO.

Table 2
Location of radio sounding sites with respect to GPS stations.

RS station	Latitude (° ′ ″)	Longitude (° ′ ″)	Height[a] (m)
SAEZ	−34 48 36.00	−58 31 12.00	20
SACO	−31 18 36.00	−64 13 12.00	474
SASA	−24 51 00.00	−65 28 48.00	1221

RS station	Shortest distance from (km)	GPS station	Number of common days	Height difference (m)
SAEZ	17	IGM1	179	−19.8
SACO	7.6	UCOR	138	36.54
SASA	9.3	UNSA	145	−3.38

[a] Mean sea level height following World Meteorological Organization (WMO) values.

The complete profile of temperature, pressure and humidity and the integration into precipitable water values [in mm] for each sounding are publicly available information at the web site of the Department of Atmospheric Sciences of the University of Wyoming (USA) (http://weather.uwyo.edu/upperair/sounding.html). Such values will be referred to in this work as Precipitable Water Vapour values from Radio Sounding (RS PWV).

The microwave observations of the operational NOAA-18 satellites allow us to retrieve vertical profiles of temperature and humidity at pressure levels using the International TOVS Processing Package (http://cimss.ssec.wisc.edu/opsats/polar/iapp/IAPP.html). This information is operationally processed at Divisão de Satélites e Sistemas Ambientais – Centro de Previsão do Tempo e Estudos Climáticos (DSA-CPTEC). A vertical integration of humidity profiles provides information over large regions covered by the satellite. It is possible to obtain a large number of products associated with humidity parameters. Among them, the PWV is evaluated in this work. The closest pixel to the different stations studied in the present work has been considered to compare with different PWV estimations (NOAA PWV). These estimations are available one or two times a day, depending on the satellite orbit. All available orbits are considered for the present analysis.

2.2. GPS data processing

The basic GPS carrier phase observation equation expresses in distance units the range between the satellite and the receiver and can be written as:

$$\boldsymbol{\Phi}_i = \rho + c(\Delta t^S - \Delta t_R) + N\lambda_i + \mathrm{IONO}_i + \mathrm{TD}_i + \varepsilon \qquad (1)$$

where ρ is the geometric distance between the satellite and station, expressed in terms of their coordinates. The following term on the right-hand side represents the clock error terms, where the superscript S refers to the satellite and the subscript R refers to the receiver at the GPS station. Thus, this second term can be separated into the satellite and receiver clock errors. The third term represents the integer carrier phase ambiguity term. It follows the respective terms for ionospheric refraction effects (IONO), tropospheric refraction effect (Tropospheric Delay, TD) and finally the measurement error (Hofmann-Wellenhof et al., 1992; Kleusberg and Teunissen, 1996).

Because the troposphere is a non-dispersive medium for radio waves propagation, the TD is independent of frequency and it cannot be removed from numerical algorithms involving frequency combinations as in the case of the ionospheric refraction effect.

As many versions of Eq. (1) could be accumulated as there are visible satellites over the horizon at the observer location at a given instant. The typical time frequency is 30 or 15 s. From careful processing of the huge amount of accumulated data over a 1 year period, the Zenith Total Tropospheric Delay (ZTD) is calculated as a function of the water vapour content integrated over the zenith of the observer.

The methodology used to obtain the ZTD requires the GPS data measurements to be processed twice. First of all, it is necessary to process the raw GPS data in order to obtain coordinates of the stations with high precision. Once the station coordinates are perfectly known, they will be input as data in a new process. Such a step is necessary in order to estimate the ZTD for each of the stations involved. The only requirement to achieve this step is to possess meteorological information (pressure, temperature and humidity) for the station. The calculation of the observations is carried out using the scientific processing package called Bernese GPS V5.0 (BSW) (Dach et al., 2007). This set of programs has being developed since the middle of the 1980s at the Astronomical Institute of University of Berne (Switzerland). The package consists of about 100 programs and more than 1000 subroutines.

In the following, we briefly introduce the main characteristics of the process over GPS observations using Bernese software. This software uses double differences in phase. It allows to eliminate the clock error of the receiver and to reduce the consequences of the clock error of satellites. Moreover, it uses a precise ephemeris combined by the IGS and it applies an ionosphere-free combination of double differences. Furthermore, we also use the ocean tide load modelling results from the FES95.2 global ocean tide models (Le Provost et al., 1998). In the first processing made for obtaining precise station coordinates, we compute the ZTD using the Saastamoinen model (Saastamoinen, 1973) along with the Niell mapping function (Niell, 1996). This *a priori* model is evaluated on the surface and extrapolated from the standard atmosphere. A correction for each station is computed every 2 h (Kaniuth et al., 1998) and added to the *a priori* zenithal delay.

Prior to the processing itself, the data must be prepared according to a delicate and laborious task: the detection and repairing of lost cycles. Although the software possesses a specialized module to perform this work, to obtain the highest quality requires a manual control of the values (Natali et al., 2002). Moreover, we apply the QIF (Quasi Ionosphere Free) in order to estimate the ambiguities according to Dach et al. (2007).

After a daily quasi-free adjustment of the whole network in order to construct the reference frame from the ephemeris, the reference frame is established by introducing a network of weighting control points. Subsequent to a second similarity transformation, the station coordinates are obtained with an accuracy better than 1 cm. These coordinates are introduced as data points in the last step of the procedure performed to get the precipitable water vapour.

2.2.1. Obtaining the GPS PWV values

This final step involves a further reprocessing of the geodetic network using the BSW software. Here, both the precise coordinates of the stations computed in the first BSW process and the satellite orbits are data values. In the output, the software calculates a ZTD for each and every station of the geodetic solved network every 30 min. The technical characteristics of this final BSW reprocessing step follow the suggestions of Duan et al. (1996) for obtaining GPS PWV.

Usually, the tropospheric error (ZTD) in GPS positioning can reach up to 2.5 m. This can be divided into the contribution of a dry component (Zenith Hydrostatic Delay, ZHD) and a wet component (Zenith Wet Delay, ZWD). Whereas ZHD is assimilated to a hydrostatic model of the troposphere and explains 90% of the total effect, ZWD is related to the PWV; it is highly variable and unpredictable

$$\mathrm{ZTD} = \mathrm{ZHD} + \mathrm{ZWD} \tag{2}$$

When characterizing the contribution of each component to the ZTD, we can add:

ZHD refers to the delay of the GPS radio signal crossing the same region through the gas molecules that constitute the troposphere assuming that this gas is in hydrostatic balance. Its value is of the order of 2 m. According to Elgered et al. (1991) and Saastamoinen (1973) it can be expressed as

$$\begin{aligned}\mathrm{ZHD} = {} & (2.2779 \pm 0.0024)P_s[1 - 0.00266\cos(2\phi) \\ & - 0.00028h]^{-1}\end{aligned} \tag{3}$$

where ZHD is in meters if the atmospheric pressure at ground level (P_s) is in millibar, with ϕ the latitude and h the height on the terrestrial reference ellipsoid in kilometres.

ZWD represents the delay in the GPS radio signal due to the effect of the present dipolar momentum of water molecules contained in the troposphere on its way to the receiver. This component is unpredictable and all models are very loose. Typical values are in the range from 0 to 0.5 m.

From the former, it is clear that ZHD can be obtained from Eq. (3) if the atmospheric pressure values of the station are known. Such data are provided by the SMN at each GPS site. Then, ZWD is computed from Eq. (2) as the difference between the ZTD obtained from the second BSW procedure and the ZHD.

Expressing the vertically integrated water vapour quantity on the receiver in terms of precipitable water, this is the length of a column of liquid equivalent to water and the PWV can be related to the ZWD by the expression:

$$\mathrm{PWV} = \Pi \mathrm{ZWD} \tag{4}$$

where ZWD is in longitude units and Π is a non-dimensional constant (Bevis et al., 1994). In particular, Π can be written as (Bevis et al., 1992):

$$\Pi = \frac{10^6}{\rho R_v \left[(k_3/T_m) + k_2'\right]} \tag{5}$$

where ρ is the liquid water density, R_v is the specific constant of water vapour in millibar ($R_v = 461.5181\ \mathrm{kg\ K}^{-1}$); $k_2' = k_2 - mk_1$ with k_1,k_2 and k_3 the well-known quantities used to compute the atmospheric refractivity (Bevis et al., 1992); $m = M_w/M_d$is the ratio between the mass mol of water vapour (M_w) and dry air (M_d). We adopt here the value $k_2' = 22.1\ \mathrm{K}/mb$ computed by Monico and Sapucci (2003). Finally, T_m refers to the mean weighted temperature of the atmosphere in degrees Kelvin. It can be defined as (Bevis et al., 1992, 1994; Duan et al., 1996):

$$T_m = \frac{\int (P_v/T)dz}{\int (P_v/T^2)dz} \tag{6}$$

where P_v is the partial water vapour pressure, T is the temperature and the integrals must be computed along the vertical path going through the atmosphere. Thus, T_m varies with time and can be estimated from surface temperature measurements (Bevis et al., 1992) or Numerical Weather Models (NWM) (Bevis et al., 1994). In particular, Bevis et al. (1992) have empirically confirmed that T_m can be approximated by the surface temperature (T_s), introducing an error less than 4% in the GPS PWV estimation from Eq. (4). Nevertheless, the estimation of T_m values using T_s data is deduced from a model that must be adjusted to the season and geographical location. In general, such models have been developed for the northern hemisphere.

2.2.2. GPS PWV values from different T_m estimations

The deduction of a value of T_m adapted to Argentina is very important at the moment of evaluating the quality of these regional estimations of PWV from GPS. We test three different ways of estimating the mean tropospheric temperature. Then we evaluate the behaviour of the different time series of GPS PWV values.

Firstly, we consider the very well-known model of Bevis (Bevis et al., 1992) to estimate T_m,

$$T_{m\ Bevis} = 70.2 + 0.72(T_s + 273.15) \tag{7}$$

where T_s is the surface temperature in degrees Kelvin.

In order to take into account some regional reference, we also apply an empirical model deduced for South America. It was determined by Sapucci et al. (2004). More specifically, the Sapucci model was deduced for Brazil, dividing the country into five regions and using nearly 90,000 radio soundings from 12 stations in different geographical regions. In particular, we use the expression:

$$T_{m\ Sapucci} = 0.613901T_s + 0.020243\mathrm{HR} + 102.815 \tag{8}$$

where T_s is the surface temperature in degrees Kelvin and HR refers to the relative humidity. This equation was originally deduced for the southern region of Brazil and the extrapolation to the northern and central parts of Argentina constitutes an acceptable estimation (Sapucci, 2008; personal communication).

Finally, we compute T_m according to its definition in Eq. (6). The solution was calculated considering the variables provided by the operational analysis of the NCEP. This analysis contains information on temperature, geopotential height and relative humidity at 26 vertical pressure levels, one degree resolution in latitude and longitude, every 6 h. Prior to the vertical integration, a bi-linear interpolation over pressure level is carried out to the location of the station. An additional interpolation between vertical pressure levels is considered over UNSA due to the altitude of the station above mean sea level. The vertical numerical integration of Eq. (6) is performed up to the height of the station by a trapezoidal method. Such an estimation is called in this work the T_m Analysis.

Once different T_m values have been obtained, it is possible to retrieve a different GPS PWV time series. The last has a temporal resolution of 1 h interval (when meteorological data are available) during the entire selected period.

3. Results

3.1. Comparison of different GPS PWV values

In this section, the behaviour of GPS PWV data is analyzed using different values of T_m for its calculation. The different PWV values are estimated as described above from different values of T_m and they are named GPS PWV T_m Bevis, GPS PWV T_m Sapucci, and GPS PWV T_m Analysis, respectively.

In order to compare the performance of different GPS PWV values computed from different T_m estimations, the differences between GPS PWV Bevis values and the GPS PWV T_m Sapucci model, and between GPS PWV T_m Bevis and GPS PWV T_m Analysis are presented in Fig. 2.

Given that the Bevis model for T_m estimation applied to GPS PWV determination is a very well-known and classical reference, both differences are referred to GPS PWV T_m Bevis. As a common feature, we can clearly see there is no a big difference from applying T_m Bevis or T_m Sapucci in the GPS PWV computation. Such a difference is of the order of 0.5 mm and it is possible to observe a sub-estimation of PWV Bevis over all stations.

The situation is quite different when applying T_m Analysis. Here the differences can reach more than 3 mm, and the sub-estimation by PWV Bevis is higher. All curves are very close in June, for the driest season especially over UCOR, UNRO and IGM1. Likewise, UNSA denotes dif-

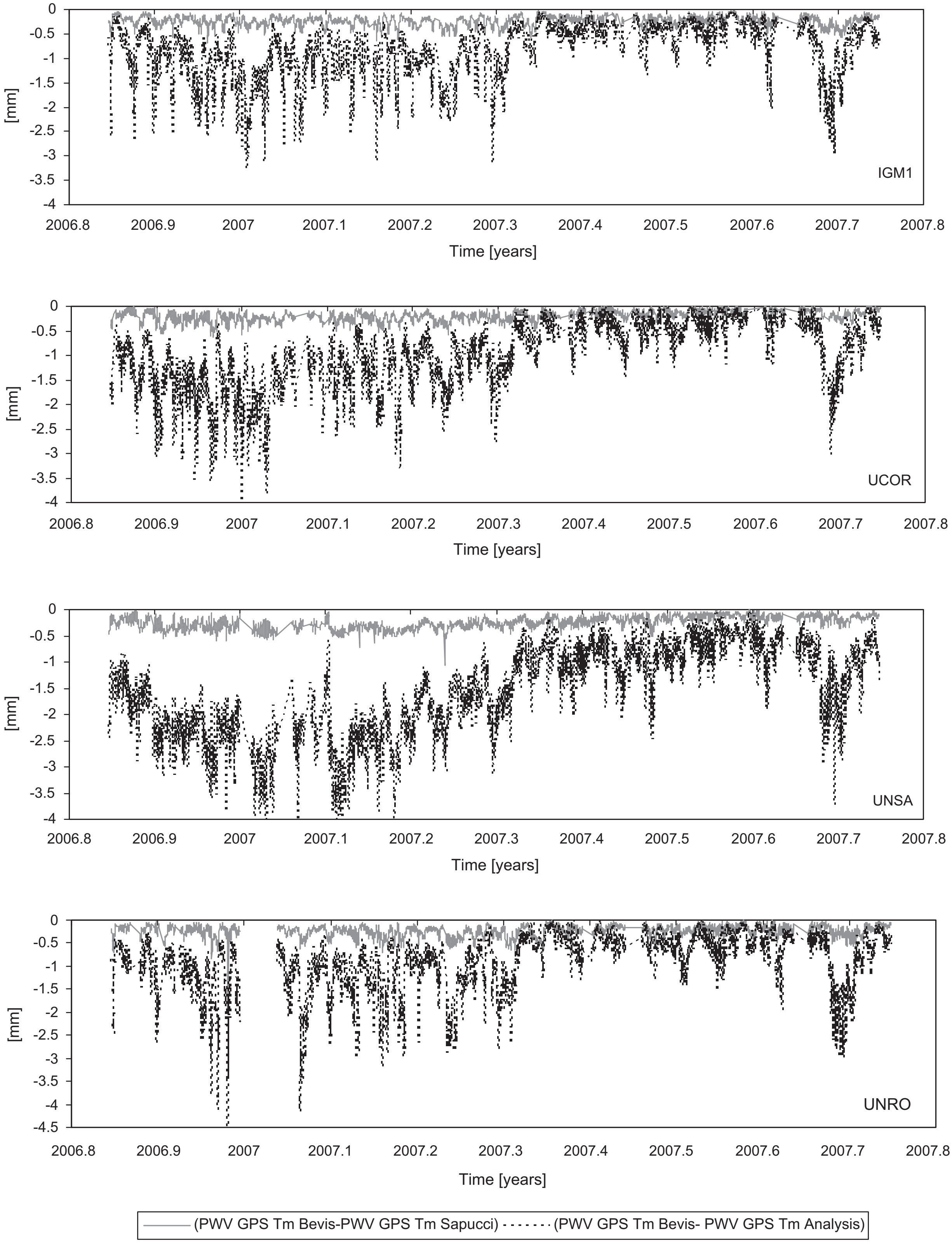

Fig. 2. Differences between GPS PWV values in [mm] computed from different T_m estimations: Bevis model, Sapucci model and calculated from NCEP Reanalysis values. The difference between GPS PWV Bevis minus GPS PWV Sapucci is represented by solid lines. In dotted lines: the difference GPS PWV Bevis minus GPS PWV Analysis.

ferences between both curves, also during June. This can be explained by considering that UNSA is elevated more than 1200 m above mean sea level in the Andes Mountains. It is widely known that information from numerical meteorological models has problems over mountain areas. A large number of factors influence the correct determination of meteorological profiles. The vertical and horizontal resolution of the models, the vertical coordinate, parameterization of radiation and topography are some factors that can influence the correct determination of variables. Thus, the numerical integration of Eq. (6) must be studied carefully over UNSA. This cause can result in an overestimation of T_m over this particular station. Extreme discrepancies appear, principally during the wet or rainy periods, when meteorological models principally fail to determine the respective variables. These differences can be observed at UNRO in the fall (March, for the southern hemisphere). During this period, the station receives an accumulated precipitation higher than 450 mm. A similar behaviour can be observed in summer (January) when UNSA also receives a high accumulated precipitation. The differences between the various values of T_m never exceeds 15 K. Nevertheless it is very important to remark that high discrepancies in the evaluation of T_m only produce small differences in the final evaluation of PWV. Considering these differences and using Eqs. (4) and (5), we estimate that discrepancies of 20 K only contribute $(10^{-2} * \mathrm{ZWD})$ to the total error in PWV.

In an attempt to determine the most suitable T_m for making a better GPS PWV estimation, we compare them with respect to the PWV from radio soundings (RS PWV). Radio sounding observations are launched every day at 11:30 UTC over Argentina, in order to reach the 5000 m levels approximately at 12 UTC. Because the balloon typically takes an hour and a half to rise up to the maximum altitude (Oolman, L., 2008, personal communication), we compute the respective GPS PWV estimate taken as the average of values inside a temporal window that includes an hour before and an hour after 12 UTC. Thus, the bias is understood as the difference between RS PWV and the respective averaged estimation of GPS PWV.

Table 3 shows the average of the differences in millimetres and the root mean square of the differences calculated between (RS PWV – GPS PWV T_m Analysis), (RS PWV – GPS PWV T_m Sapucci) and (RS PWV – GPS PWV T_m Bevis), respectively. The correlation coefficient (ρ) between RS PWV and GPS PWV computed from the different T_m is also given. Provided that the different ρ's vary in the second decimal figure, just one value of the correlation coefficient is given and it is considered the same for the three different T_m estimations. From Table 3, we can see that all differences between GPS PWV values and RS PWV are close to 1 mm, which is expected (Elgered et al., 1997; Niell et al., 2001; Dai et al., 2002; Li et al., 2003; Deblonde et al., 2005). The correlation coefficients present values higher than 0.9 over all stations with available radio sounding data. The dispersions are similar at different stations. It is important to notice that the UNSA station only has available radio soundings during the wet season, which is from December until March.

The GPS PWV variations between (T_m Bevis – T_m Analysis) shown in Fig. 2 are of the order of 3–4 mm in summer. Thus, during the moist and rainy periods, the application of T_m Analysis appears to be the best option for the northern and central part of Argentina. However, Table 3 does not suggest a large difference in using GPS PWV estimated from the numerical integration of NCEP variables (GPS PWV T_m Analysis). Besides, there is no big advantage in using the Sapucci model either, which was originally created for the southern part of Brazil.

For all the reasons given, we conclude that the estimation of mean tropospheric temperature according to the well-known Bevis model is a simple and acceptable choice for this regional study. Nevertheless, the investigation of a regional empirical model better adapted to the geographical and climatic characteristics of the applied area would be necessary in more accurate determinations.

3.2. GPS PWV validation

Inter-comparisons have been made among the three datasets for time series measurements using data collected over Argentina: PWV values integrated from radio soundings at 12 UTC; PWV retrieved from NOAA-18 satellite products, which are available once or twice a day depending on the orbit; and GPS PWV using T_m values estimated from the Bevis model calculated every hour. Because of the different time intervals of the data series, GPS PWV values are computed around the RS PWV or NOAA PWV instant. In the first case, the GPS averaged values include three points (one hour before and one hour after) of the radio sounding determination. In the second case, the GPS PWV values are linearly interpolated from the hourly value closest to the NOAA PWV instant.

It is important to remark on the different importance of these comparisons. On the one hand, the comparison between PWV values estimated from GPS observations and from radio sounding determinations is carried out in

Table 3
Comparison of PWV from radio sounding measurements (RS PWV) with PWV from GPS observations computed using different strategies for the mean tropospheric temperature (T_m): Sapucci model (Sapucci), Bevis model (Bevis) and numerical integration of operational variables from NCEP Analysis (Analysis). N refers to the number of samples and ρ is the correlation coefficient. Radio sonde values are not available from near Rosario (UNRO station).

	N	ρ	Mean difference (mm)			σ of the differences (mm)		
			Analysis	Sapucci	Bevis	Analysis	Sapucci	Bevis
IGM1	282	0.98	−1.21	−1.00	−0.75	2.06	2.04	2.04
UCOR	174	0.95	0.35	0.76	0.87	2.72	2.60	2.58
UNSA	86	0.94	−1.04	0.36	0.70	2.04	1.51	1.50

order to validate the quality and performance of the regional GPS PWV computation presented in this work. On the other hand, the comparison between PWV values computed from NOAA-18 satellite data and GPS PWV estimations gives us the opportunity of analyzing the quality of a data set which is not a classical product of the NOAA-18 mission.

Fig. 3 shows the GPS PWV values estimated from T_m computed from the Bevis model (PWV GPS T_m Bevis) and the PWV determined from radio soundings (RS PWV). From these figures, very good agreement can be observed between the RS PWV and GPS PWV over all stations. The performance of the GPS PWV estimation can also be evaluated from the results of Table 3. The correlation between both data time series is very good and the r.m.s. of the differences is about 2 mm.

The reason for this could be the mechanism of the radio soundings observation. In general the radio sounding observation is considered at a fixed point as the balloon is ascending vertically. In fact, this could be a source of mistakes when one fulfils a point analysis. The complete radio sounding takes approximately an hour and a half to obtain the complete vertical profile. During this time, the balloon can move several kilometres relative to its launching position by the wind in the medium and high levels of the atmosphere. This is because it is generally

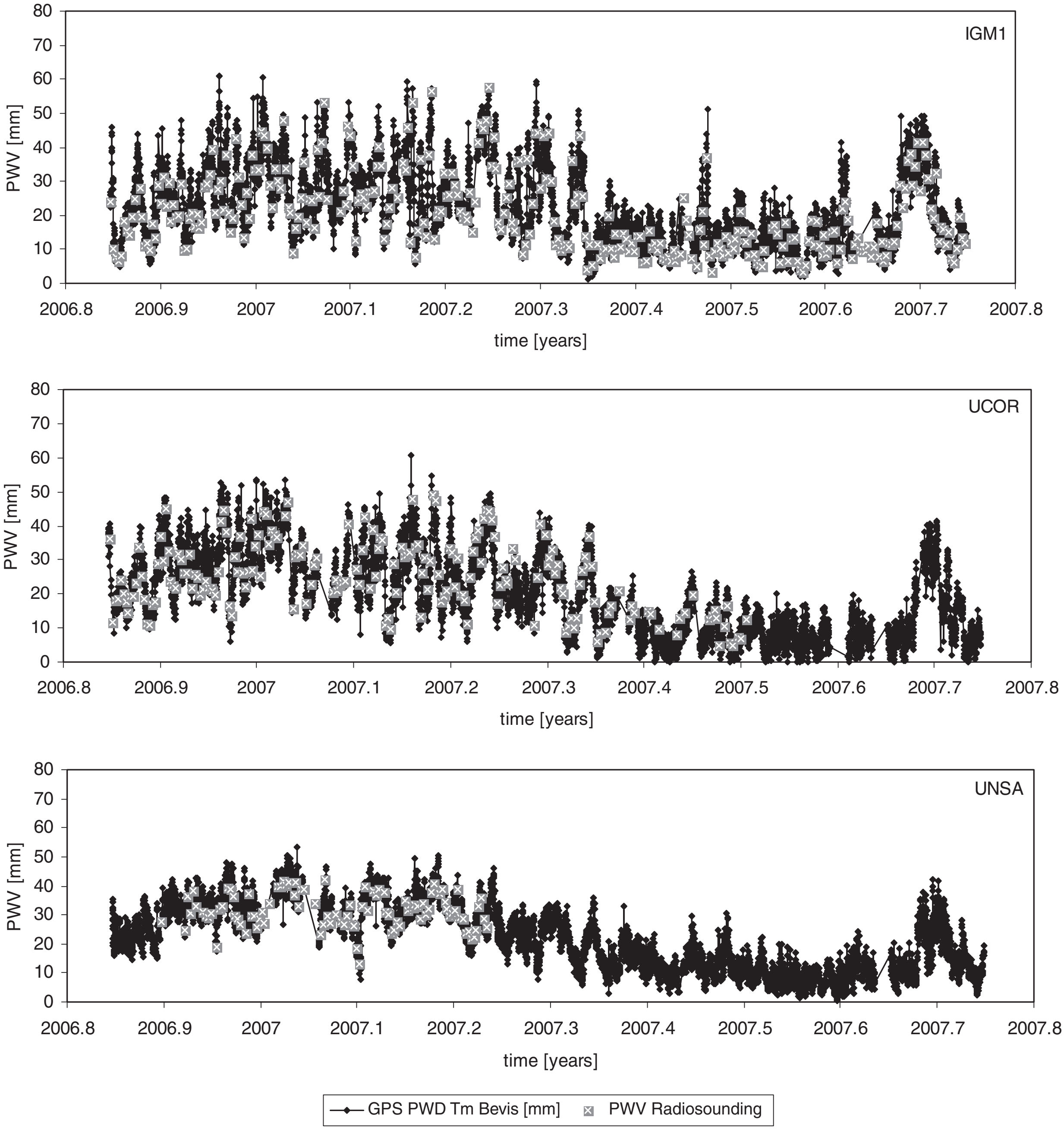

Fig. 3. GPS PWV estimated from T_m computed from Bevis model (PWV GPS T_m Bevis) and PWV determined from radio sounding (RS PWV).

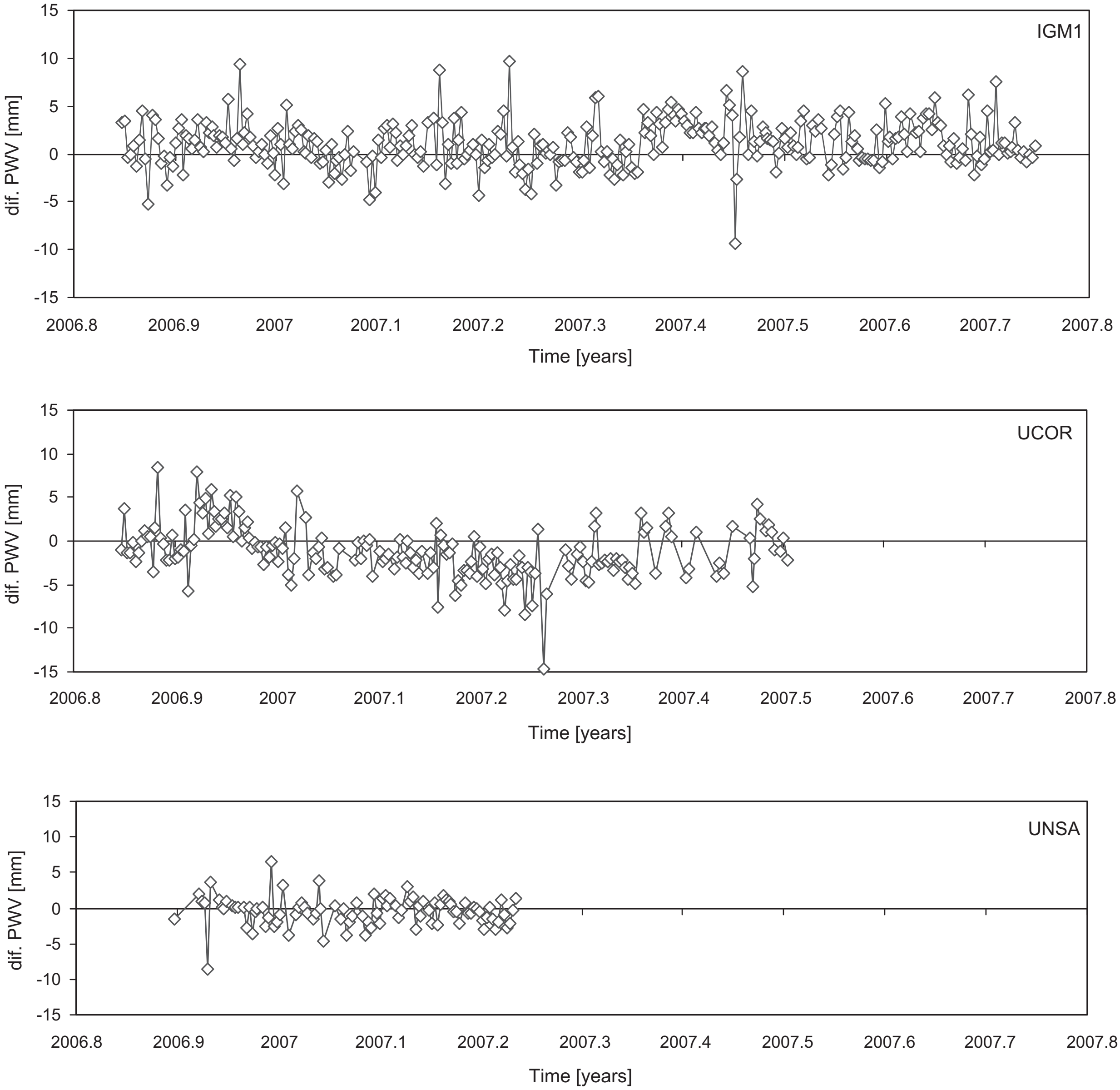

Fig. 4. Differences between GPS PWV using T_m estimated from Bevis model (PWV GPS T_m Bevis) and RS PWV measured at Buenos Aires, Córdoba and Salta, respectively.

accepted that a radio sounding is representative of a horizontal area of 100 km in diameter about the point of observation (WMO, 1996). This postulate is often not true and, taking into account non-homogeneities or differences in topography, this means is that observation is not constant over the swapped area.

If we consider the RS PWV values as a reference, the GPS determination seems to overestimate the PWV values. This feature is particularly noticeable in the high precipitation period during summer. However, the reason is that the RS PWV time series is bare in comparison with GPS PWV.

The former analysis is presented graphically in Figs. 4 and 5. Fig. 4 shows the differences between GPS PWV and the respective RS values. Fig. 5 presents scatter plots showing the variation of GPS PWV values derived from the T_m computed from the Bevis model (PWV GPS T_m Bevis) compared to the PWV values from radio sounding measurements (RS PWV). Here again, a correlation higher than 0.9 can be observed.

Fig. 6 shows the monthly mean of the PWV values from GPS observations computed from the T_m estimated from the Bevis model (GPS PWV Bevis) and the monthly mean of PWS determinations from radio soundings (RS PWV). The dotted line represents the annual mean of GPS PWV Bevis. The annual cycle of the variable is clearly depicted in GPS PWV Bevis, with a minimum over the winter period. The extreme monthly value is observed at UNSA in January, while the dry season is depicted at all stations during the austral winter (June–August). The monthly means are similar but the GPS data overestimate the precipitable water vapour content over UNSA during the entire rainy period when radio soundings are available.

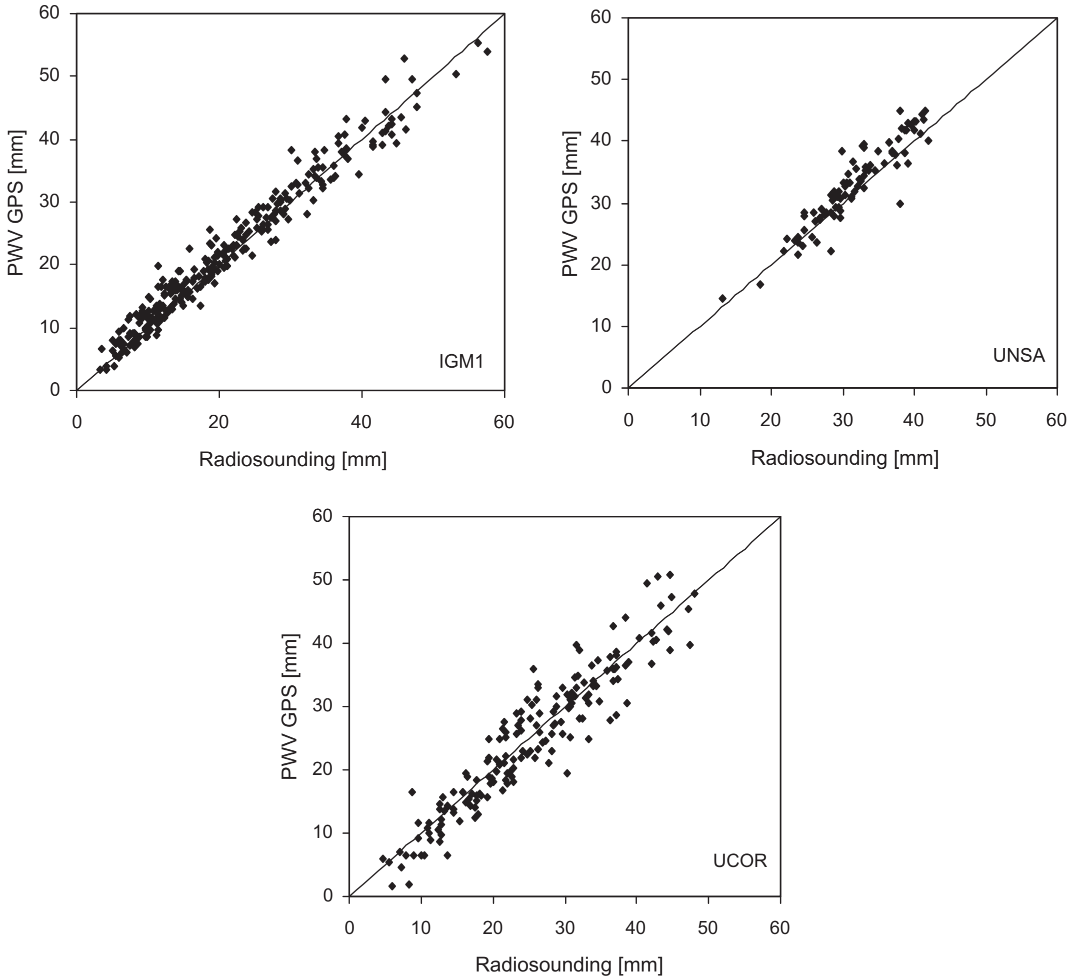

Fig. 5. Scatter plots showing the variation of GPS PWV values derived from T_m computed from Bevis model (PWV GPS T_m Bevis) compared to the PWV values from radio sounding measurements (RS PWV).

It is important to point out that Argentinean radio sondes are launched once a day and they are of the Vaisala RS-80 type. Thus, the results shown in Fig. 5 agree with recent studies over large regions of the northern hemisphere which demonstrated that a radio sounding launch frequency of twice a day may introduce a bias of up to 3% of the mean PWV values (Stoew and Elgered, 2005). Besides, investigations on the performance of the Vaisala RS-80 relative humidity sensor have suggested an age-related contamination by the packaging of the sondes. Consequently, a correction algorithm is necessary in very humid conditions when the Vaisala RS-80 underestimates the measurement by as much as 5% (Lesht, 1999; Niell et al., 2001; Stoew and Elgered, 2005 and authors therein).

Fig. 7 shows the GPS PWV values estimated from the T_m computed from the Bevis model (PWV GPS T_m Bevis) along with the PWV values computed from NOAA-18 mission data (NOAA PWV).

NOAA PWV values are corrected for cloudiness. The correction algorithm follows (Ceballos et al., 2004) and evaluates the presence or absence of cloudiness. The NOAA PVW estimation must be masked by the presence of clouds due to the fact that the estimation of temperature and humidity profile is incorrect from microwave channels. Thus, we consider a limit on the water vapour in the infrared channel and also in the visible channel during diurnal observations. Further information about the algorithm can be found in Ceballos et al. (2004).

Likewise, NOAA PWV values present fairly good agreement with the GPS PWV estimation, although the NOAA PWV time series is sparse, considering that the satellite has only two observations per day over the area. The former can be clearly seen in Fig. 8. This shows the difference between the computed GPS PWV and NOAA PWV determinations. Note that some extreme values are as large as 20 mm. Fig. 9 shows a persistent error in NOAA PWV which has a tendency to overestimate the values especially over UCOR and IGM1. While correlation coefficients are acceptable, it is necessary to further evaluate the potential for improved cloud mask to compare a set of observations with better quality.

Although observations from satellites are an invaluable tool because of the extended area covered by sensors, it is still necessary to continue the search for an algorithm that calculates accurately estimations of meteorological variables, principally those variables related to humidity.

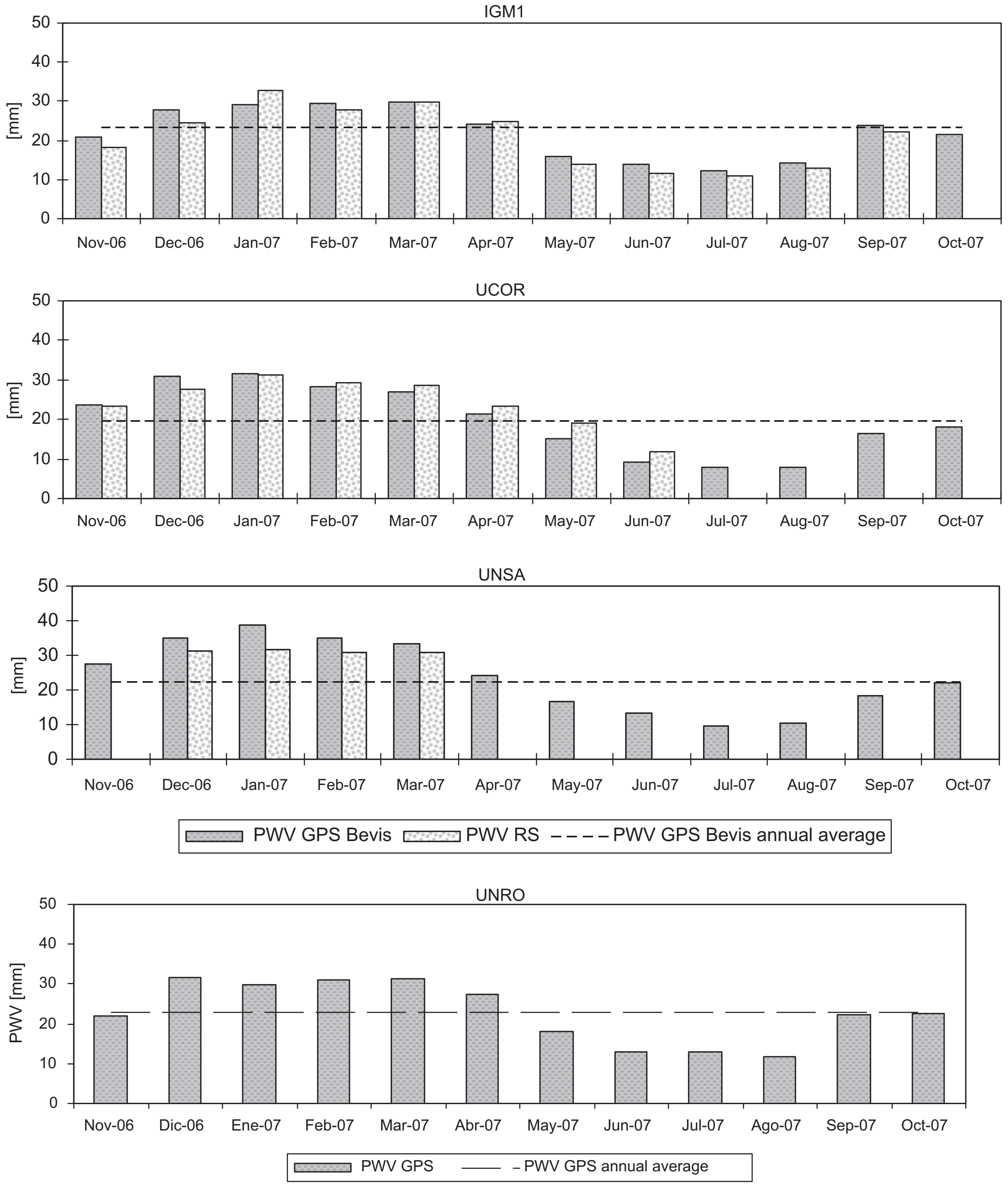

Fig. 6. Monthly mean of PWV values from GPS observations computed from T_m estimated from Bevis model (PWV GPS T_m Bevis) and monthly mean of PWS determinations from radio soundings (RS PWV). The dotted line represents the annual mean of GPS PWV Bevis. Notice that there is no radio sounding available near the UNRO station.

NOAA PWV tends to overestimate the total water vapour content in the atmosphere but captures the tendency of this variable. From this affirmation it is important to make progress with the calibration and evaluation of data retrieved over a longer period of time and from a large number of stations around the area. In this sense, the GPS PWV estimation could be considered to be a source of reference data. On the other hand, temperature profile estimations from NOAA show that the information from over Argentina presents acceptable errors for data assimilation or meteorological operational tasks (de Souza et al., 2005).

4. Discussion

In this work, we study the behaviour of the GPS PWV computed at four stations in Argentina, applying different

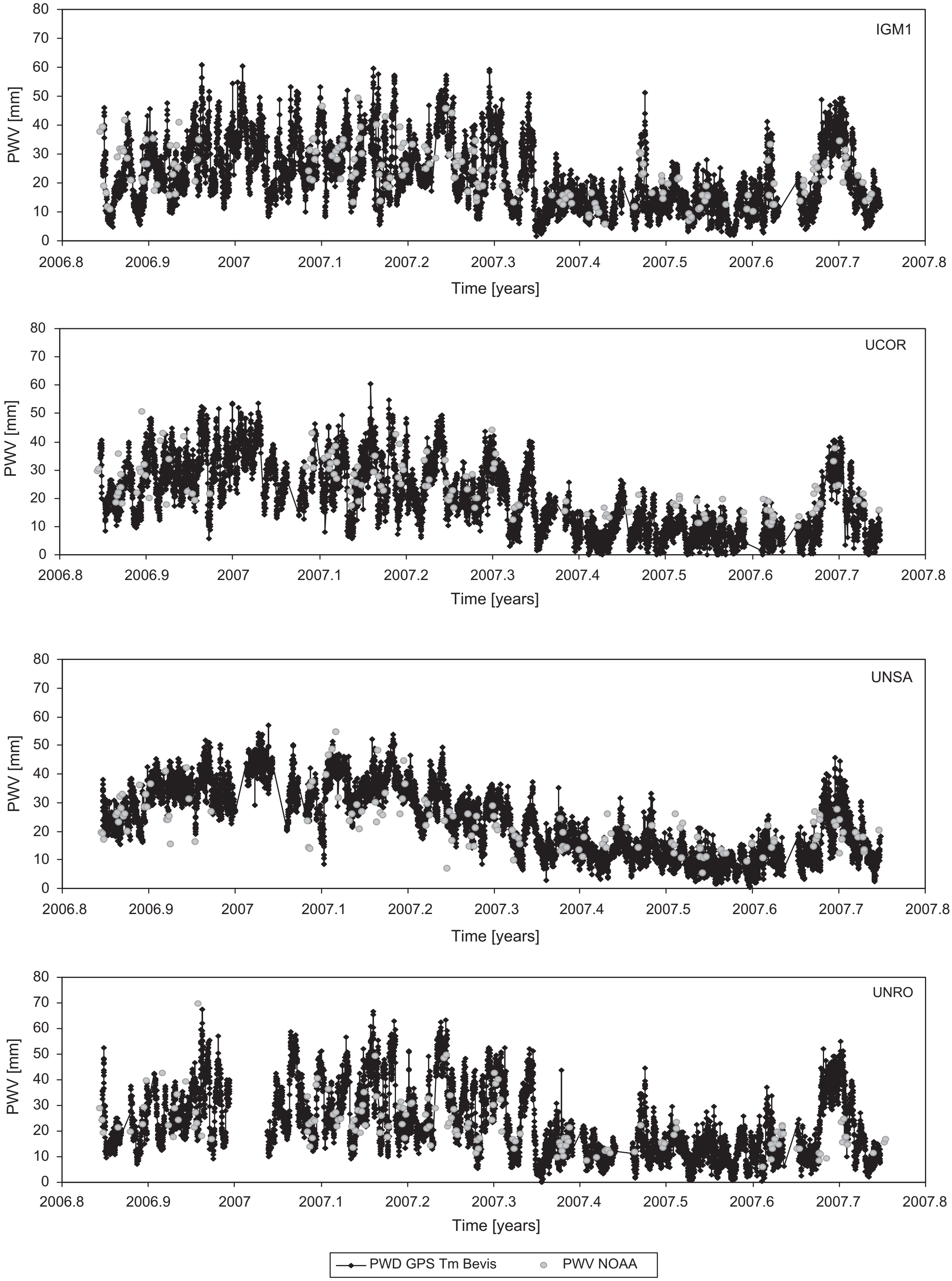

Fig. 7. GPS PWV estimated from T_m computed from Bevis model (PWV GPS T_m Bevis) and PWV values from NOAA-18 mission (NOAA PWV).

T_m estimations: using the well-known model of Bevis et al. (1992); calculating T_m with Eq. (6) as the numerical integration of operational variables provided by the NCEP; and extrapolating the empirical model proposed by Sapucci et al. (2004). Differences in T_m are of the order of 15 K, but this only produces small differences in the final

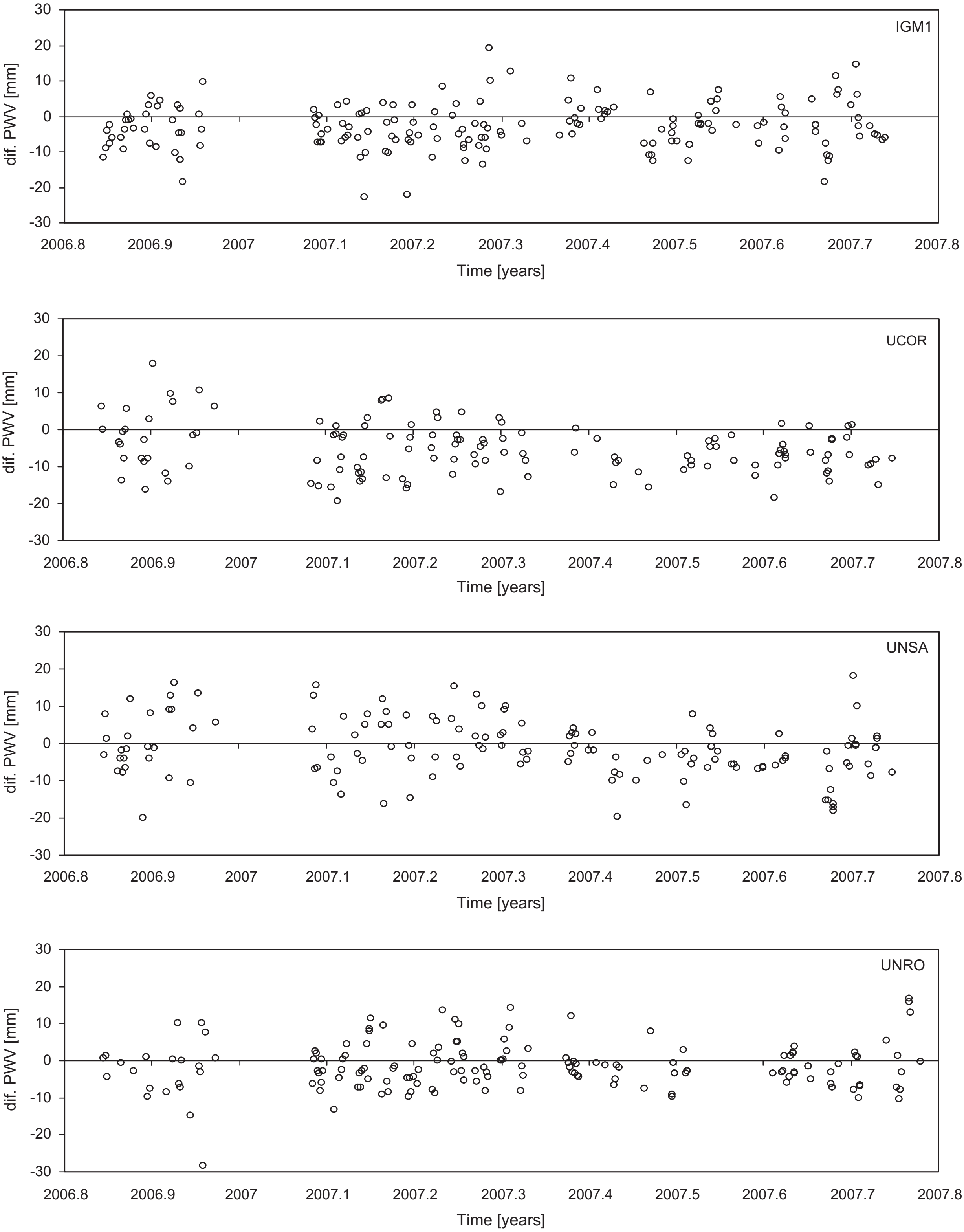

Fig. 8. Differences between GPS PWV using T_m estimated from Bevis model (PWV GPS T_m Bevis) and NOAA-18 PWV values.

evaluation of PWV. The interpolation of the model of Sapucci for the northern, central and eastern part of Argentina is acceptable during the dry periods. Moreover, the computation of GPS PWV using the classical model of Bevis, originally deduced for the northern hemisphere, shows similar behaviour to the Sapucci model inside 0.5 mm. The differences between GPS PWV estimated with T_m from Sapucci or Bevis with respect to T_m Analysis can be as large

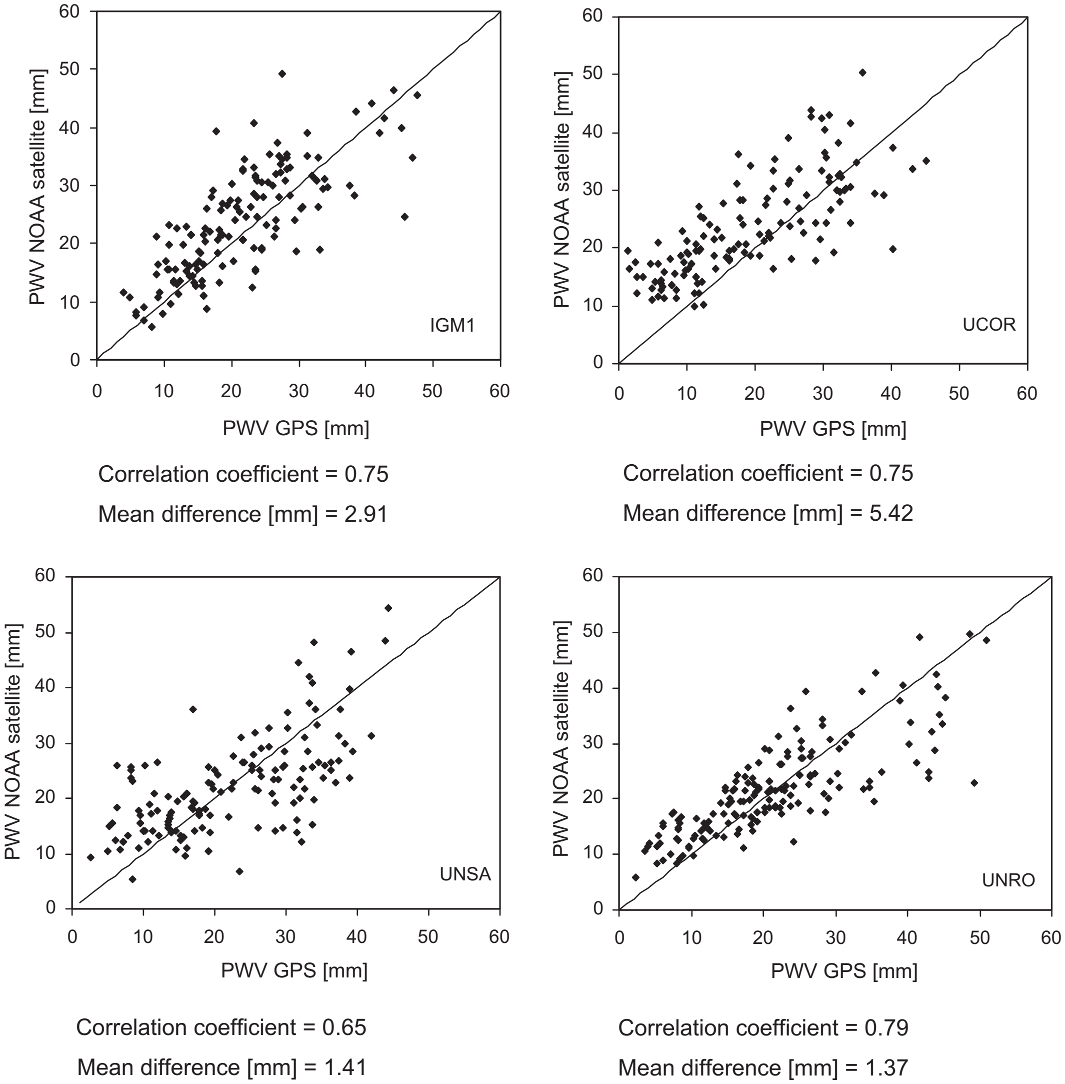

Fig. 9. Scatter plots showing the variation of PWV determinations from measurements of NOAA-18 satellite compared to GPS PWV values derived from T_m values computed from the Bevis model (GPS PWV T_m Bevis).

as 3 mm during wet or very rainy periods. However, this behaviour does not imply an improvement of GPS PWV T_m Analysis over other GPS PWV estimations. In fact, from Table 3 the comparison of the time series of differences between radio soundings and different GPS PWV time series shows similar results for the 3 GPS PWV estimations.

Thus, we conclude that the usage of T_m estimated from the Bevis model is the best choice for regional studies unless some more studies taking into account the geographical and climatological characteristics of the region are performed. Such studies would bring a suitable model of T_m better adapted to this area. To validate the GPS PWV values, we consider the RS PWV measurements as a reference. There is excellent agreement between the GPS PWV values and RS PWV time series. As expected, the mean average of the differences are of the order of 1 mm. and the correlation coefficients are higher than 0.9 for all stations.

Finally, the NOAA PWV values are compared with respect to GPS PWV. NOAA PWV tends to overestimate the total water vapour content in the atmosphere but captures the tendency of this variable. Although the performance of NOAA PWV is not adequate compared to the precision showed by the values obtained with GPS, often they constitute the only accessible data source in this vast territory (i.e. UNRO station). Because the determination of PWV is not the mean product of the NOAA-18 satellite mission, these results show the potential of such a product. In this sense, it is important to make progress with the calibration and evaluation of data retrieval over a longer period of time and the GPS PWV estimation could be considered as a source of reference data.

Provided that the radio soundings are sparse, generally once a day and linked to important airports, the GPS PWV constitutes a reliable and economic alternative for obtaining important information for meteorology applications, especially for its use in operational activities and data assimilation in numerical weather models.

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