A global, 2-hourly atmospheric precipitable water dataset from IGS ground-based GPS measurements: Scientific applications and Future needs

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Abstract

A 2-hourly data set of atmospheric precipitable water (PW) has been produced from ground-based Global Positioning System (GPS) measurements of zenith tropospheric delay (ZTD, also called zenith path delay ZPD) by using the 2-hourly IGS tropospheric product. The PW data are available every two hours at about 80-268 International GNSS Service (IGS) ground stations from 1997 to 2004. An analysis technique is developed to convert ZTD to PW on a global scale. Special efforts are made on deriving surface pressure (Ps) and water-vapor-weighted atmospheric mean temperature (Tm). Ps is derived from global, 3-hourly surface synoptic observations with temporal and vertical adjustments. Tm is calculated from NCEP/NCAR reanalysis with temporal, vertical and horizontal interpolations. The PW dataset is validated by comparing with radiosonde, microwave radiometer (MWR) and satellite data. The comparisons show no significant and systematic bias in the GPS-derived PW data. The scientific applications of the PW dataset include studying the diurnal variations in PW over the globe, quantifying spatial and temporal inhomogeneity and biases in global radiosonde PW data and estimating the diurnal sampling errors in twice-daily radiosonde humidity. The new 5-minute IGS ZTD product available at all IGS stations will be explored in the future work.

Based on our experience with the IGS tropospheric product, we would like to make the following recommendations on improving future IGS products. (1) The long-term stability (consistency in time) is crucial for the application of IGS PW data in climate monitoring studies. Every effort should be made to maintain the consistency of ZTD data in time, including minimizing changes in both instruments and analysis methods. (2) It is very important to investigate various biases in the ZTD product with special emphasis on diurnal biases, such as diurnal mapping function errors. Among the existing water vapor datasets on a global scale, only GPS-estimated PW dataset can provide sufficient temporal resolution to resolve the diurnal cycle of the atmosphere. Diurnal biases in ZTD would result in spurious PW diurnal variations. (3) The surface meteorology sensors with at minimum accurate pressure measurements at all IGS stations would be very useful for calculating the dry delay and removing atmospheric pressure loading of the earth surface. Especially as the 5-min ZTD data become available, the high resolution surface pressure data are required to derive the 5-min PW data. In addition, the IGS surface met sensors need to be regularly maintained and calibrated; the data need to be carefully quality controlled. Current limited IGS surface met data bear various problems. (4) We recommend that some future IGS stations be co-located with the future reference radiosonde network for cross-validation and improving mapping function models. (5) We suggest that in the future the IGS products can be better documented by incorporating details on data characteristics, how they were derived and user-friendly metadata.

1. Introduction

Water vapor plays a central role in atmospheric radiation, the hydrological cycle and in understanding and predicting global climate change. Therefore, it is vital to advance the understanding of water vapor variability and change, but such advancement is hampered by inadequate observations. Observations of atmospheric water vapor have traditionally been taken through balloon-borne radiosondes. Unfortunately, the usefulness of radiosonde data in climate studies is limited, in part, by sensor characteristics that vary substantially in time and space. Several studies and reports have called for creating global water vapor datasets with sufficient accuracy and temporal resolution, and more importantly long-term stability. None of existing radiosonde, satellite or blended datasets can meet the requirements for the new water vapor datasets.

Since the early 1990's, considerable efforts have been devoted to derive PW using ground-based Global Positioning System (GPS) measurements at high temporal-resolution (5 minutes to two hours). The advantages of GPS-derived PW data include continuous measurements, availability under all weather conditions, high accuracy (<2 mm in PW), long-term stability and low cost [Ware et al., 2000]. GPS-derived PW has broad applications, including validating radiosonde, satellite and reanalysis data [e.g., Guerova et al., 2003; Hagemann et al., 2003; Li et al., 2003; Dietrich et al., 2004; Van Baelen et al., 2005], improving numeric weather prediction [e.g., Kuo et al., 1993; Gutman et al., 2004; Gendt et al., 2004], studying diurnal variations of PW [Dai et al., 2002; Wu et al., 2003], and monitoring climate change [e.g., Gradinarsky et al., 2002]. Although there have been many regional applications of ground-based GPS data [see Dai et al., 2002], there have been only a couple of studies to take advantage of the growing network of the International GNSS Service (IGS) stations around the globe [Beutler et al., 1999; Hagemann et al., 2003; Deblone et al., 2005].

This study represents a first attempt to use the existing and expanding IGS station measurements of zenith tropospheric delay (ZTD) to derive a long-term PW data set on a global scale for climate and weather applications. The analysis technique to derive PW from ZTD on a global scale and the PW dataset are presented in Wang et al. [2006] and only briefly summarized here. This paper will present some preliminary results on scientific applications of this dataset and make some recommendations on future needs of IGS tropospheric product based on our experience. We will present two scientific applications, (1) quantifying time- and space-dependent biases in global radiosonde humidity records, and (2) documenting and understanding PW diurnal variations.

2. Data and Analysis Method

This study starts with the IGS 2-hourly ZTD data (the legacy tropospheric product). The 2-hourly ZTD data are available from 1997 at ~100 stations to 2004 at ~335 stations, are centered at odd UTC hours (01, 03, …, 21 UTC) (Fig. 1), and can be downloaded on-line from three IGS data archive centers with about 2~4-week delay from real-time. An analysis technique was developed to convert ZTD to PW on a global scale and summarized in Figure 2 [Wang et al. 2005, 2006]. Surface pressure (Ps) and water-vapor-weighted atmospheric mean temperature (Tm) are two key parameters for this conversion. Ps is derived from global, 3-hourly surface synoptic observations with temporal and vertical adjustments. Tm is calculated from NCEP/NCAR reanalysis with temporal, vertical and horizontal interpolations.

The analysis technique was applied to the 2-hourly ZTD data to create a near-global, 2-hourly PW dataset. The number of stations for each month in the PW data is about 7 to 70 less than that in the original ZTD data set because the Ps data are unavailable at those stations. Our final product is a 2-hourly PW dataset at 01, 03, 05, …, 23 UTC from 1 February 1997 to 31 December 2004 at 80 to 268 stations around the globe (Fig. 1). The product also includes 2-hourly surface pressure and temperature derived from the synoptic observations, Tm from the NCEP/NCAR reanalysis, original ZTD, and calculated ZHD and ZWD.

The PW dataset is validated by comparing with radiosonde, microwave radiometer (MWR) and satellite data. The comparisons show no systematic bias in the GPS-derived PW data. The GPS and radiosonde PW comparisons at 102 stations around the globe show mean difference of 1.03 mm (drier for radiosonde data) with a mean standard deviation of differences of 1.93 mm. The bias is primarily due to known dry biases in the radiosonde data. The latitudinal and seasonal variations of PW derived from the GPS data agree well with that from International Satellite Cloud Climatology Project (ISCCP) data if the ISCCP data are sampled only at grid boxes containing GPS stations.

3. Scientific Applications: Quantifying time- and space-dependent biases in global radiosonde humidity records

Global radiosonde dataset has been and will continue to be a valuable resource for study long-term climate variations, but its role in climate study is limited by sensor characteristics that vary substantially with time and space. Our motivation is to see whether GPS data can be used as an independent data source to characterize the errors/biases in global radiosonde data.

In the GPS PW dataset and a global radiosonde dataset (The Integrated Global Radiosonde Archive, IGRA, see Durre et al., 2005) for 2003 and 2004, we found 102 stations where GPS and radiosonde stations are located within 50 km and have elevation differences less than 100 m. The GPS PW values within an hour of radiosonde launch times are compared with those from radiosondes at the 102 stations. Figure 3 shows mean PW differences (IGRA-GPS) at 102 stations for ten types of radiosondes, which are used at 98% of global radiosonde stations. The first three types are Vaisala radiosonde, which is used at ~51% of global radiosonde stations. At sixty-five out of total 78 stations where Vaisala radiosondes are launched, radiosonde PW values are systematically lower than that from the GPS data, implying a dry bias in the radiosonde data. The dry bias in Vaisala radiosondes is well known [cf. Wang et al., 2002]. MRZ/Mars (Russian radiosonde) and IM-MK3 (India radiosonde) show systematic moist biases (Fig. 3). MRZ/Mars uses the goldbeater's skin as its humidity sensor, which has slow response and results in a moist bias. IM-MK3 uses the carbon hygristor, which tends to have a low-level moist bias [Ceisielski et al., 2003]. To our knowledge this is the first time that a single, independent dataset is able to show the radiosonde humidity bias on a global scale.

One of the biggest problems in using radiosonde data in the climate study is the inhomogeneity of radiosonde data records due to the constant changes in radiosonde instruments and reporting practice. The PW comparison between GPS and radiosonde is shown in Fig. 4 for 2003 in Miami, FL. The differences are random and within 5 mm. However, if the comparison is done for 1998, the difference in the last half of the year is similar to that in 2003, but radiosonde data are consistently moister than GPS in the first half of the year. This is due to the change of radiosonde types from VIZ to Vaisala RS80H on June 1, 1998. The carbon hygristor used in VIZ has a moist bias. This example demonstrates the potential of using GPS-PW data to identify discontinuity in radiosonde data.

4. Scientific Applications: Documenting and Understanding PW Diurnal Variations

The diurnal cycle is one of the most important climate signals, but there is lack of data with sufficient temporal resolution to study diurnal variations of water vapor. So the 2-hourly GPS-derived PW can fill this gap. Seasonal mean diurnal anomalies are presented in four regions: Europe, 30°-70°S, Northern Hemisphere (NH) Mountains and Darwin as examples for studying diurnal PW variations using our 2-hourly PW dataset (Fig. 5). Europe has the densest GPS network with 110 stations. The PW diurnal cycle in Europe is strongest in summer with amplitude of ~0.6 mm and is slightly weaker in fall and winter, but is negligible in spring. The PW in Europe peaks at noon, late afternoon (1600-1800 LST) and early evening (2000-2200 LST) in winter, fall and summer, respectively. The PW diurnal cycle in 30°-70°S, NH Mountains and Darwin has similar phase in four seasons but different amplitudes. The 30°-70°S has the smallest diurnal cycle, while Darwin region has the largest one with peak-to-peak amplitude of larger than 2 mm. In the mountain region PW peaks from late afternoon to early evening and has the largest diurnal cycle in summer. More and detailed analyses will be done in the future including understanding observed diurnal variations. PW Diurnal cycle is controlled by precipitation, large scale vertical air motion, surface evaportranspiration, wind direction (for coast area) and other factors [Dai et al., 2002].

5. Future Needs

Based on our experience with the IGS ZTD product, we would like to make the following recommendations on improving future IGS tropospheric products.

5.1 To maintain long-term stability and high quality of the ZTD product

Maintaining long-term stability is very important for the application of the ZTD product in the climate study. For long-term climate applications, the lack of consistency over time in the legacy ZTD product is of a particular concern as it results from occasional changes made by individual ACs in their GPS data handling (e.g., different elevation cutoff angles, revised antenna phase maps) and their ZTD estimation algorithms (e.g., new mapping functions, different constraint schemes on the analysis parameters) [Byun et al., 2005].

The quality of the legacy ZTD data is also a concern for us. As we know that the legacy ZTD product is a combination of ZTD solutions from 7 ACs. If the solutions from different ACs do not agree, you might get some noisy data. Figure 6 shows the time series of PW and ZTD from day 280-320 in 1999. There are unrealistic spikes in both PW and ZTD values. They are associated with large standard deviations of ZTD. Therefore we rejected ZTD data with the standard deviation greater than 15 mm. This simple criterion is proved very efficient in removing most of the spikes in the ZTD data.

Starting from October 2000, the 5-minute ZTD data at all IGS sites are also produced using the precise point positioning approach [Byun et al., 2005; Humphreys et al., 2005]. The new GPS product is superior to the 2-hourly legacy product in many ways, including higher accuracy, long-term stability, higher temporal resolution and more stations [Byun et al., 2005]. We are planning to use the new tropospheric product in the future if IGS is committed to deliver the product continuously.

5.2 To reduce diurnal biases in the ZTD product

One of important applications of 2-hrly GPS-derived PW dataset is studying diurnal variations of PW, so the diurnal bias in ZTD should be minimized. Figure 8 shows the PW difference between GPS and MWR at three stations, Toulouse, Darwin and Onsala (Sweden). Despite the magnitude difference, all three sites show the similar phase, dry GPS data before noon, but moister after noon. This is plausibly due to diurnal mapping function errors as suggested by Humphreys et al. [2005], but needs to be verified. Note that five out of all seven ACs use the mapping function from Niell [1996], which does not include mapping function variations on time scales less than one year. However, whether the diurnal mapping function error causes the diurnal variations of PW differences between GPS and MWR needs to be verified by using an alternative mapping function and see how the GPS estimates of PW change [Todd Humphreys, personal communication].

The diurnal bias in Tm can directly introduce diurnal bias in PW. The Bevis Tm_Ts relationship is commonly used to derive Tm [Bevis et al., 1992]. Wang et al. [2005] evaluated the Bevis relationship by comparing with Tm calculated from ERA-40 reanalysis data. Tm derived from the Bevis relationship (referred to as Tmb) has a cold bias in the Tropics and subtropics (-1 ~ -6 K, largest in marine stratiform cloud regions) and a warm bias in the middle and high latitudes (2-5 K, largest over mountain regions). The random error in Tmb is much smaller than the bias. A serious problem in Tmb is its erroneous large diurnal cycle owing to diurnally invariant Tm-Ts relationship and large Ts diurnal variations, which could result in a spurious diurnal cycle in GPS-derived PW and cause 1-2% day-night biases in GPS-based PW. Therefore, we calculate Tm using the reanalysis data in our analysis method.

5.3 To improve and increase sfc-met data

The surface meteorology data, especially surface pressure, are very useful for calculating the dry delay and removing atmospheric pressure loading. Currently there are ~70 IGS stations that provide surface meteorology data. However, surface met data are very noisy and can not be used without careful examination and quality control. Fig. 8 shows the surface pressure from December 1999 to March 2002 at Brussels, Belgium from GPS surface met and surface synoptic data. Obviously something is wrong with the surface met data from October 1999 to July 2000. Based on the data log files at Brussels, we found that the surface pressure sensor was not working properly during this period, so the pressure sensor was changed on July 20, 2000. Besides improving the quality of surface met data, we also need more stations with surface met sensors, especially with the availability of 5-min ZTD data since only surface met data can provide 5-min surface pressure data to calculate ZHD. In addition, co-located surface met data can be very useful for climate process studies.

5.4 To co-locate with radiosonde stations

As shown in Section 3, the GPS-PW dataset is valuable to monitor the quality of radiosonde humidity data. However, the displacements of GPS and radiosonde stations in space can make the comparisons complicated. Figure 9 shows the comparisons of PW from GPS and radiosonde on Oct. 21-25, 2003 in La Jolla, CA. GPS and radiosonde stations are only 9 km apart and have elevations of 134 m and 69 m, respectively. For five out of total nine cases, radiosonde PW is larger than that from GPS by 5 mm or more (Fig. 9a). The detail temperature and relative humidity (RH) profiles blow 2 km in Fig. 9b and 9c show strong near surface inversions for some soundings. The large RH and warm temperature near surface contribute significantly to PW, so PW is calculated from the whole radiosonde profiles and only the profiles above the inversions (Fig. 9d). Qualitatively the PW difference between these two cases corresponds well with the PW difference between radiosonde and GPS in Fig. 9a. The near surface inversion is unique for the radiosonde station, i.e. a local feature, so nearby GPS station might not have this feature. This example suggests that we should be very careful about the comparison between radiosonde and GPS if the stations are not co-located; and in the future it is very important to co-locate GPS and RAOB stations. Such co-location is beneficial to both GPS data processing and radiosonde data quality control. Radiosonde data can be used to derive the mapping function for GPS data processing; GPS data can be used to monitor the quality of radiosonde humidity data both on real-time and in post-processing.

5.5 To increase the spatial and temporal coverage

The IGS network shown in Fig. 1 has a sparse spatial coverage, which can introduce systematic bias in global/hemispheric mean values based on our comparisons with the ISCCP PW dataset. Therefore we would like to recommend adding more IGS stations and combining other regional GPS networks to the IGS network. Total number of 2-hourly PW data points at each station for 2003 is shown in Fig. 10. Total 4380 data points are expected for a complete 2-hourly sampling. However, only 45% of stations have more than 3500 data points. The incomplete temporal coverage would make it difficult to calculate monthly, seasonally or even annual mean values. In the future, reasons for missing data should be explored, and special efforts should be made to improve the temporal coverage of the IGS ZTD data.

5.6 To better document the IGS products

We would like to recommend that in the future IGS can better document the IGS products by (1) including details on data characteristics and how they were derived, and maintaining comprehensive meta data to document any changes in instruments, data processing and others, and (3) making all documents visible to users.

6. Summary

A global, 2-hourly PW dataset is created using the IGS 2-hourly ZTD data and is available at every two hours at about 80-268 IGS ground stations from 1997 to 2004. The dataset has various scientific applications in both climate and weather researches. Two scientific applications are included here: quantifying spatial and temporal inhomogeneity and biases in global radiosonde PW data and studying the diurnal variations in PW over the globe. Based on our experiences with the IGS ZTD data, we made the following recommendations to improve the future IGS products:

1) To maintain long-term stability and high quality of the ZTD product
2) To reduce diurnal biases in the ZTD product
3) To improve and increase surface meteorological data
4) To co-locate with radiosonde stations

5) To increase the spatial and temporal coverage
6) To better document the IGS products

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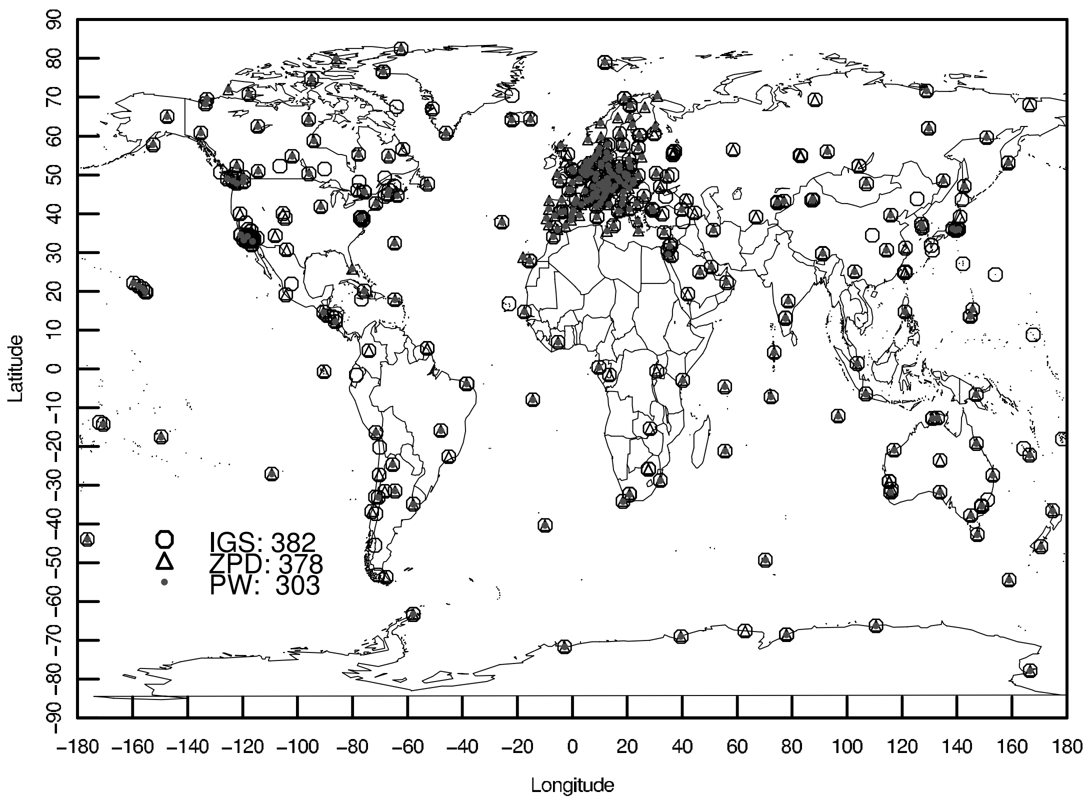

Figure 1. Geographic distribution of all IGS stations as of Feb. 10, 2006 (circle) and the stations with ZTD data (triangle), and with PW data (dot) in 2004.

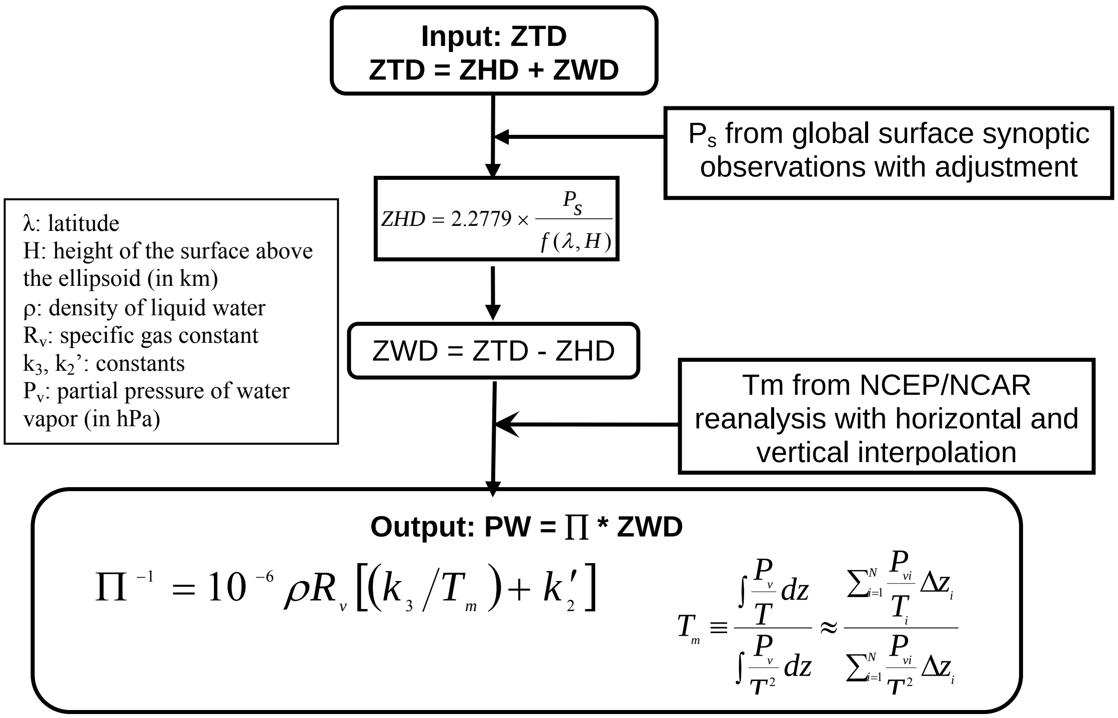

Figure 2. Schematic diagram of the analysis procedure to derive PW from ZTD (see the text for details). The parameters are defined in the left text box.

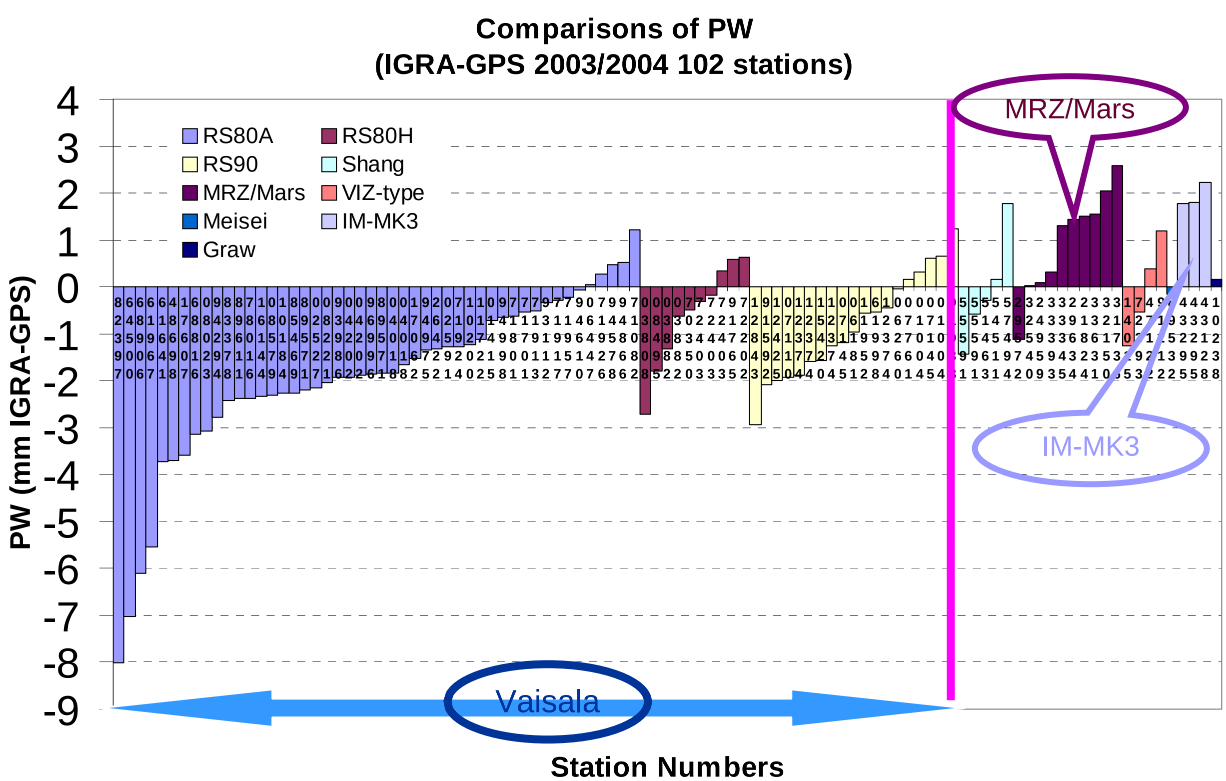

Fig. 3 Median PW differences between radiosonde (IGRA) and GPS at 102 stations using data in 2003 and 2004 for ten types of radiosondes.

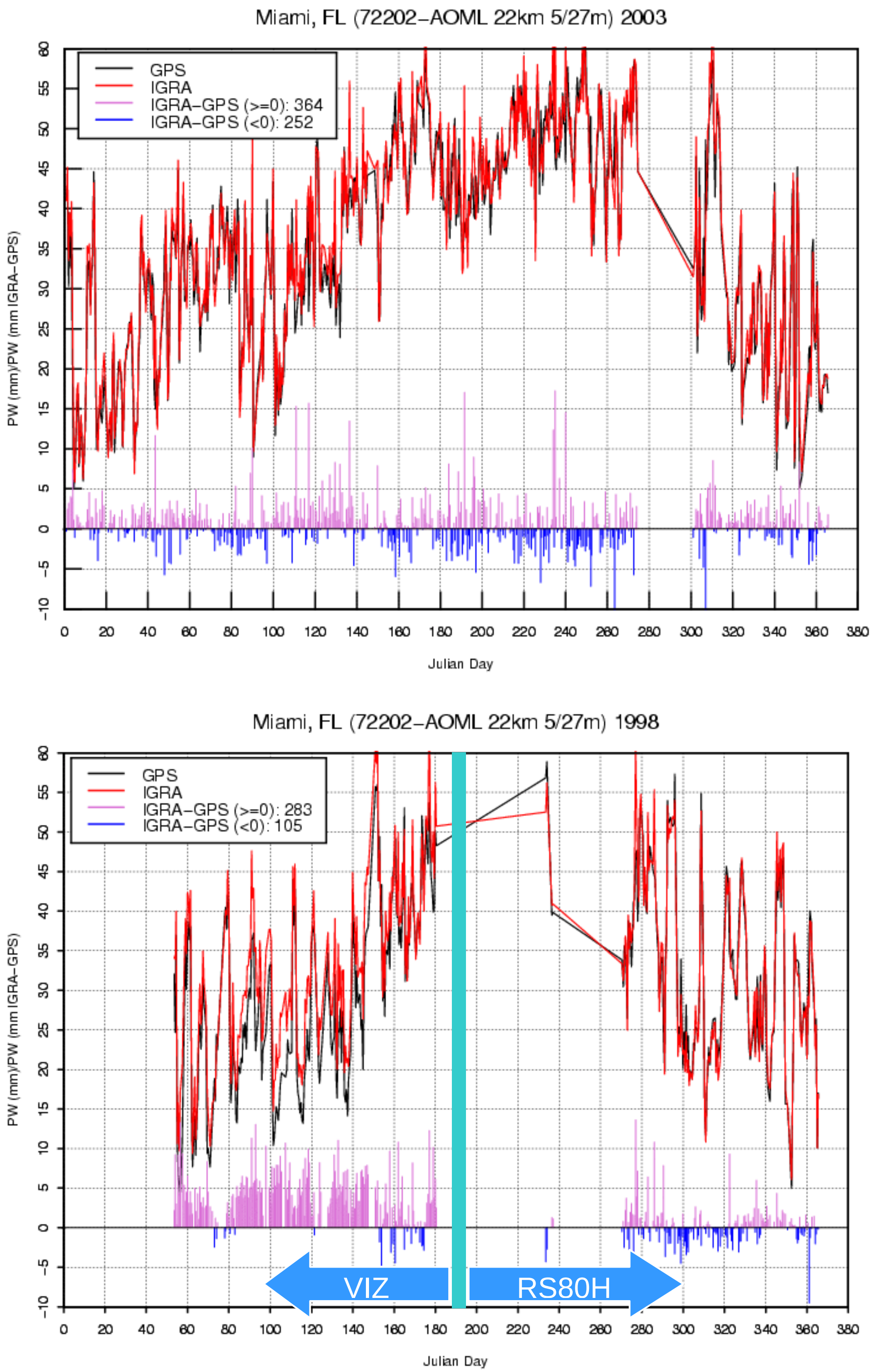

Fig. 4 Time series of PW from radiosonde (red lines) and GPS (black lines) data and PW differences (Radiosonde-GPS, magenta and blue bars for positive and negative values, respectively) for 2003 (upper panel) and 1998 (lower panel).

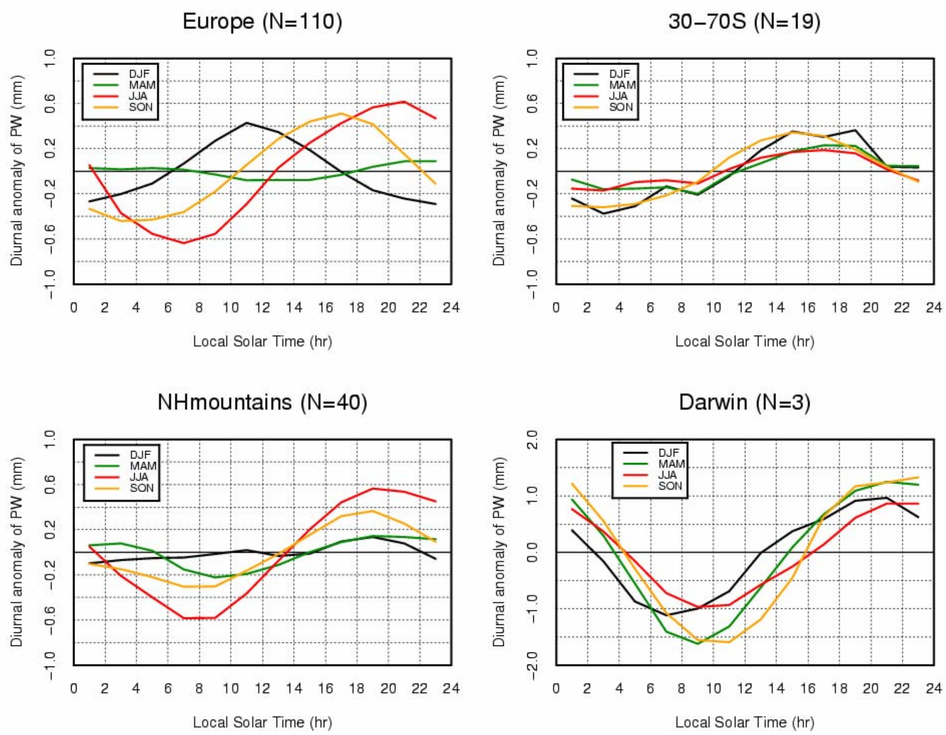

Fig. 5 Seasonal-mean diurnal anomaly of PW in four regions (Europe, 30º-70ºS, Northern Hemisphere Mountains, Darwin) and in four seasons.

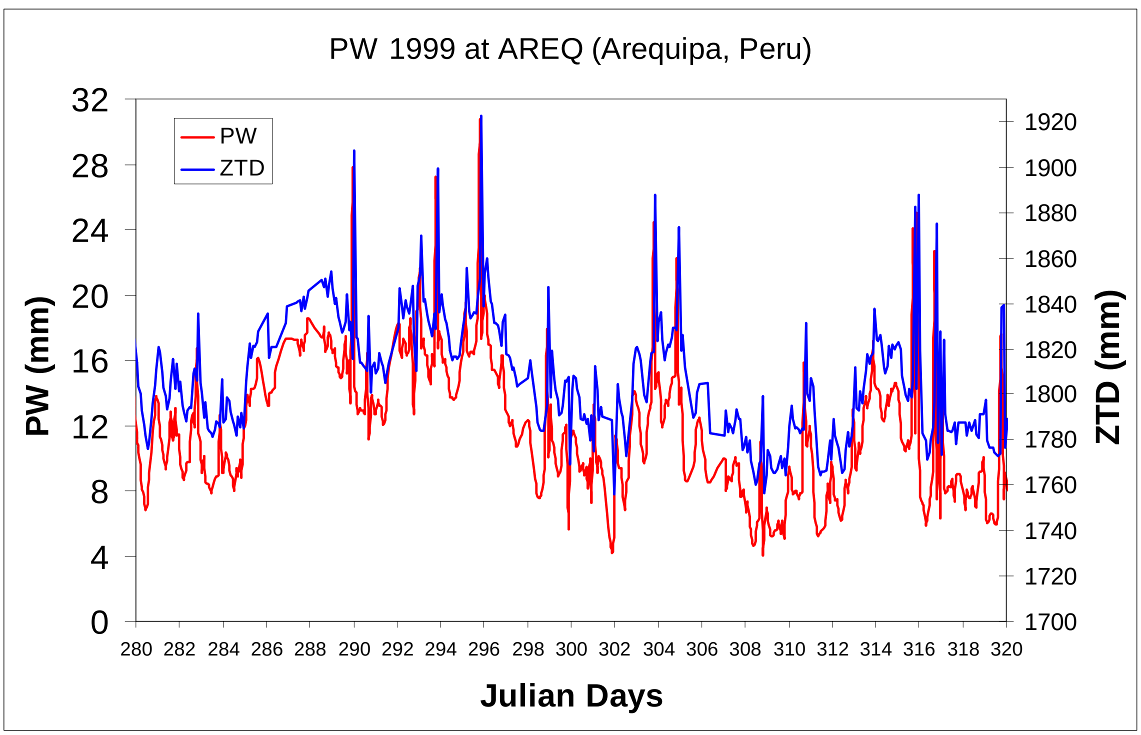

Fig. 6 Time series of PW (red lines) and ZTD (blue lines) at AREQ from Julian days 280 to 320 in 1999.

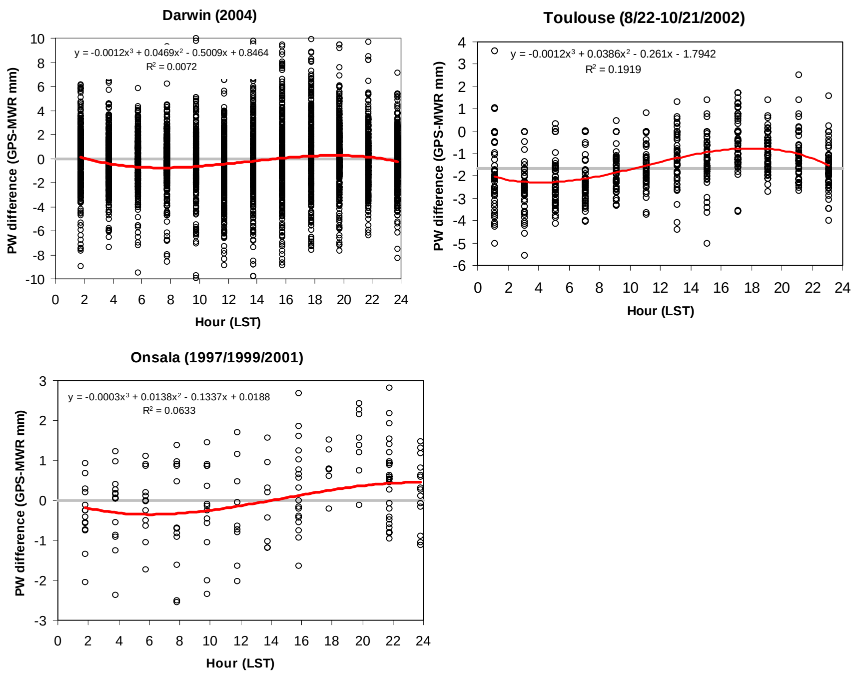

Fig. 7 Diurnal variations of PW differences between GPS and MWR (GPS-MWR) at three sites. Circles are individual data points, and red lines are the fourth-order polynomial.

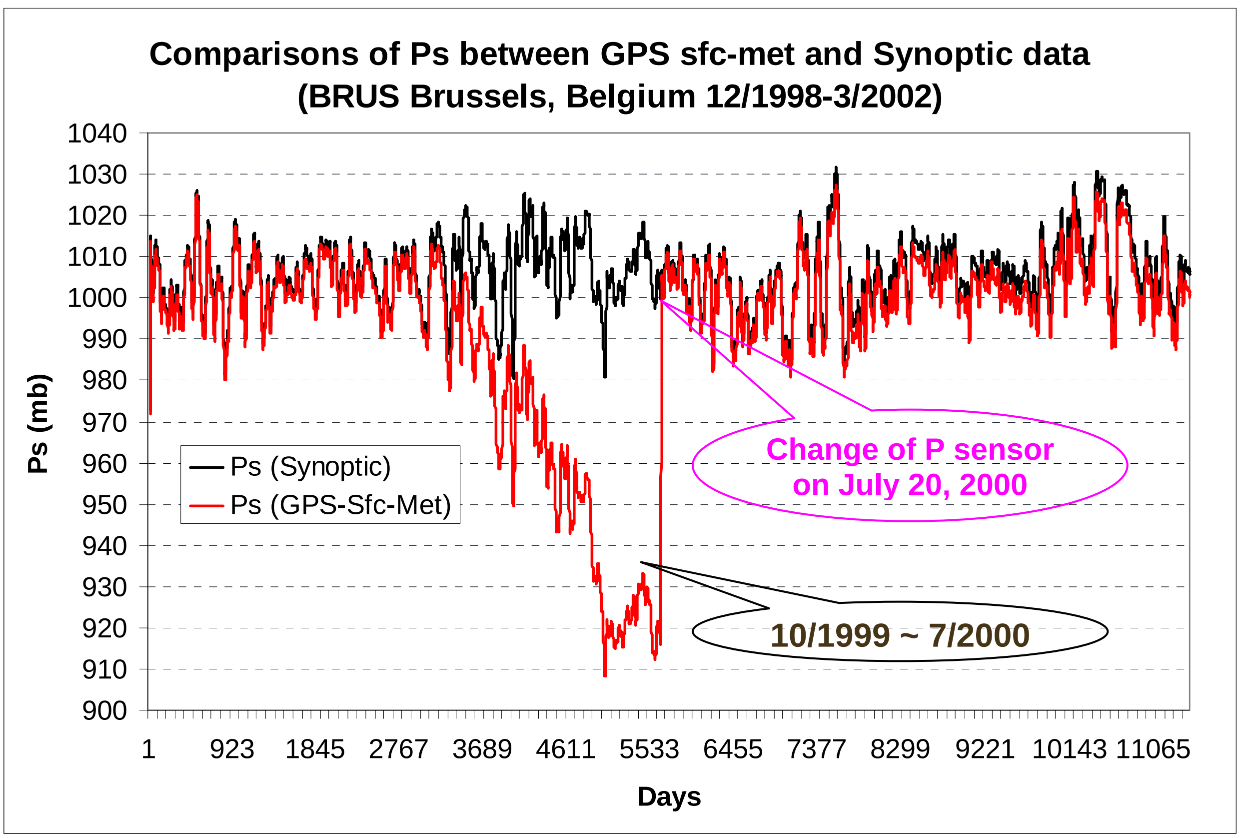

Fig. 8 Surface pressure from synoptic data (black line) and GPS surface met (red line) data from December 1998 to March 2002 at Brussels, Belgium.

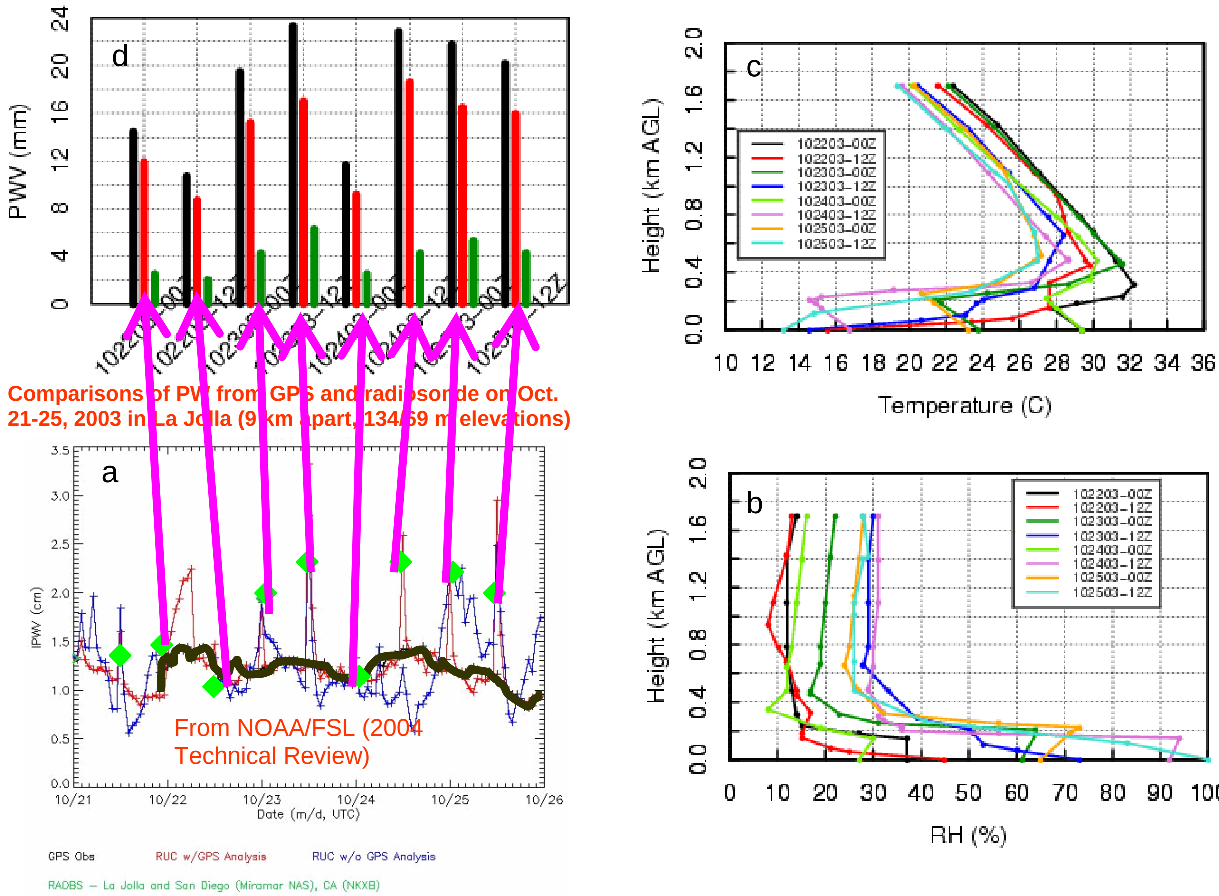

Fig. 9 Panel a shows the comparisons of PW from GPS (black line) and radiosonde (green diamonds) data on Oct. 21-25, 2003 in La Jolla, CA. Panels b and c show RH and temperature profiles below 2 km for nine soundings. Panel d displays PW calculated from the whole profiles (black bars) and from the profiles excluding the near surface temperature inversion layers shown in Panel c (red bars), and PW differences between two cases.

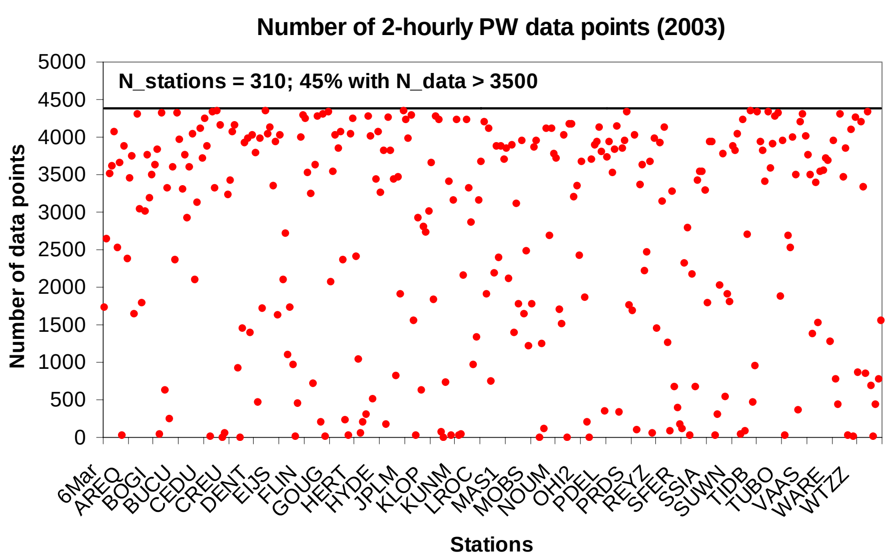

Fig. 10 Number of available 2-hourly PW data points at 310 stations in 2003.