J Geod (2009) 83:209–217
DOI 10.1007/s00190-008-0238-5

ORIGINAL ARTICLE

Climate applications of a global, 2-hourly atmospheric precipitable water dataset derived from IGS tropospheric products

Junhong Wang · Liangying Zhang

Received: 21 December 2007 / Accepted: 2 June 2008

Abstract A global, 2-hourly atmospheric precipitable water (PW) dataset is produced from ground-based GPS measurements of zenith tropospheric delay (ZTD) using the International Global Navigation Satellite Systems (GNSS) Service (IGS) tropospheric products (∼80–370 stations, 1997–2006) and US SuomiNet product (169 stations, 2003–2006). The climate applications of the GPS PW dataset are highlighted in this study. Firstly, the GPS PW dataset is used as a reference to validate radiosonde and atmospheric reanalysis data. Three types of systematic errors in global radiosonde PW data are quantified based on comparisons with the GPS PW data, including measurement biases for each of the fourteen radiosonde types along with their characteristics, long-term temporal inhomogeneity and diurnal sampling errors of once and twice daily radiosonde data. The comparisons between the GPS PW data and three reanalysis products, namely the NCEP-NCAR (NNR), ECMWF 40-year (ERA-40) and Japanese reanalyses (JRA), show that the elevation difference between the reanalysis grid box and the GPS station is the primary cause of the PW difference. Secondly, the PW diurnal variations are documented using the 2-hourly GPS PW dataset. The PW diurnal cycle has an annual-mean, peak-to-peak amplitude of 0.66, 0.53 and 1.11 mm for the globe, Northern Hemisphere, and Southern Hemisphere, respectively, with the time of the peak ranging from noon to late evening depending on the season and region. Preliminary analyses suggest that the PW diurnal cycle in Europe is poorly represented in the NNR and JRA products. Several recommendations are made for future improvements of IGS products for climate applications.

Keywords GPS · Water vapor · Climate · IGS · Zenith troposphere delay

The National Center for Atmospheric Research is sponsored by the National Science Foundation.

J. Wang (✉) · L. Zhang
National Center for Atmospheric Research (NCAR/EOL), P.O. Box 3000 Boulder, CO 80307, USA
e-mail: junhong@ucar.edu

1 Introduction

Water vapor plays a key role in atmospheric radiation, the hydrological cycle and in understanding and predicting global climate change. Therefore it is vital to advance our understanding of water vapor variability, but such advancement is hampered by inadequate observations. Observations of atmospheric water vapor have traditionally been made using 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 the creation of global water vapor datasets with sufficient accuracy and temporal resolution, and, more importantly, long-term stability (e.g., GCOS 2004; CCSP 2005; Trenberth et al. 2005). None of the existing radiosonde, satellite or blended datasets can meet these requirements.

There have been considerable efforts in deriving atmospheric precipitable water (PW) using ground-based Global Positioning System (GPS) measurements at high temporal resolution. The advantages of the GPS-derived PW data include continuous measurements, availability under all weather conditions, high accuracy (<3 mm in PW), long-term stability and low cost, all of which make the GPS PW data very compelling for climate studies (Ware et al. 2000). However, the climate applications of the GPS-derived PW data have not been fully explored because of the lack of a global, long-term and continually updated GPS PW dataset.

Although there have been many regional analyses of ground-based GPS PW data (e.g., Dai et al. 2002), there have been only a few studies (e.g., Hagemann et al. 2003; Deblonde et al. 2005) that take advantage of the growing network of the International Global Navigation Satellite Systems (GNSS) Service (IGS) stations around the globe, and the readily available zenith tropospheric delay (ZTD) data computed by the IGS (Beutler et al. 1999).

Since 2004 there has been a project to create a global, 2-hourly PW dataset from ground-based GPS measurements and to use this dataset for a variety of scientific studies, with a focus on its climate applications. A comprehensive analysis technique has been developed to convert the ZTD to PW on a global scale (Wang et al. 2005, 2007). The technique was applied to the global IGS ZTD data to produce a global, 2-hourly PW data set (Wang et al. 2007). Some of the applications of this dataset were highlighted in Wang et al. (2007). In addition, Wang and Zhang (2008) describe an application of this dataset to characterize systematic errors of global radiosonde PW data. The analysis technique and the updated global, 10-year (1997–2006), 2-hourly GPS PW dataset are first briefly described in Sect. 2. Then two climate applications of the dataset are presented, namely evaluating radiosonde and reanalysis PW data (Sect. 3), and studying PW diurnal variations and comparing them with the reanalysis data (Sect. 4). In Sect. 5, several recommendations are made on improving future IGS tropospheric products for climate applications.

2 Data and analysis method

The IGS ZTD data are available from 1997 (at ∼100 stations) to 2006 (at 451 stations), at 2-hourly resolution before November 2006 and 5-min resolution afterwards. The ZTD data can be downloaded from three IGS data archive centers with about 2 ∼ 4-week delay from real-time. The 5-min ZTD data are linearly interpolated to the 2-hourly resolution. An analysis technique was developed to convert the ZTD to the PW on a global scale, and is summarized in Wang et al. (2005, 2007). Surface pressure (Ps) and water-vapor-weighted atmospheric mean temperature (Tm) are two key parameters for this conversion. The ZTD is a sum of the zenith hydrostatic delay (ZHD) and wet delay (ZWD). The ZHD can be estimated from Ps; the ZWD is a function of PW and Tm. Ps was derived from global, 3-hourly surface synoptic observations with temporal and vertical adjustments. Tm was calculated from the NCEP/NCAR reanalysis with temporal, vertical and horizontal interpolations.

The analysis technique was applied to the 2-hourly ZTD data to create a global, 2-hourly PW dataset for the period from 1997 to 2004 (Wang et al. 2007). After Wang et al. (2007), the PW dataset has been updated to December 2006 and will continue to be updated as other auxiliary data become available. The PW data are available every two hours (0100, 0300, 0500, …, 2300 UTC) from 80 to 370 IGS ground stations. In addition, the GPS ZTD product from the U.S. SuomiNet regional network has been processed using the same technique. As a result, the GPS PW data at an additional 169 stations in the contiguous US for 2003–2006 are added to the global PW dataset. Figure 1 shows that the number of stations in 2006 in the PW dataset is 539, with 370 IGS and 169 SuomiNet stations. The PW dataset was compared with radiosonde, microwave radiometer, and satellite data in Wang et al. (2007). The comparisons did not reveal any systematic bias in the GPS PW data and show a root-mean-squared (rms) error of less than 3 mm. The PW dataset also consists of 2-hourly surface pressure derived from the synoptic observations, Tm from the NCEP/NCAR reanalysis, original ZTD, and calculated ZHD and ZWD.

The Integrated Global Radiosonde Archive (IGRA) produced by the National Climatic Data Center (NCDC) (Durre et al. 2006) are matched and compared with the GPS PW dataset in Wang and Zhang (2008) and in this study. Three atmospheric reanalysis products, the National Center for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) (NNR), the European Centre for Medium-Range Weather Forecasts (ECMWF) 40-year (ERA-40), and the Japanese Reanalysis (JRA), are matched in time and space and compared with the GPS PW data. The reanalysis data are available at 6-hourly resolution (0000, 0600, 1200, 1800 UTC) for the period of this study (1997–2006), except ERA40, which is unavailable after August 2002.

3 Evaluation of radiosonde and reanalysis PW data

Global radiosonde data have been and will continue to be a valuable resource for weather prediction and studying

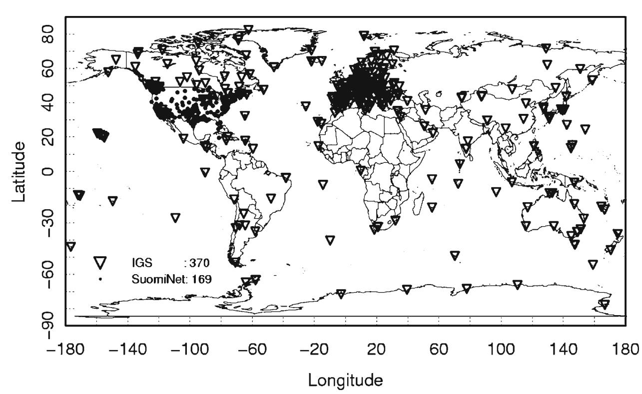

Fig. 1 Geographic distribution of all IGS stations (*triangle*) and the SuomiNet stations (*dot*) with PW data available in 2006

long-term climate variations, but its climate applications are limited by sensor characteristics that vary substantially with time and space. Our motivation was to determine whether the GPS PW data can be used as an independent data source to characterize and possibly correct the biases in global radiosonde humidity data. The reanalysis generates a comprehensive global, multi-decadal dataset using a constant state-of-art numerical data assimilation technique with various past observations. The atmospheric reanalysis data are useful for a variety of climate and weather research applications. The GPS data have not been assimilated in any of the reanalysis products, so they are independent data sources for validating the reanalysis products.

The PW comparisons between radiosonde and GPS at ∼130 global radiosonde stations were presented in Wang and Zhang (2008) and are only briefly summarized below. New results (Figs. 2, 4) show comparisons at two US stations and at three stations with the full 10-year (1997–2006) GPS record, and are described below. In Wang and Zhang (2008), for the first time, three types of systematic errors in global radiosonde PW data are quantified, including measurement biases of the 14 radiosonde types along with their characteristics, long-term temporal inhomogeneity and diurnal sampling errors of once and twice daily radiosonde data. Fourteen types of radiosondes use three types of humidity sensors: capacitive polymer, carbon hygristor and Goldbeater's skin. The capacitive polymer generally shows mean dry bias of −1.19 mm (−6.8%) with larger magnitudes during the day than at night, especially for Vaisala RS90 and RS92 radiosondes. On the other hand, the carbon hygristor and Goldbeater's skin hygrometers have mean moist biases of 1.01 mm (3.4%) and 0.76 mm (5.4%), respectively. The time series of monthly mean PW differences between the radiosonde and GPS are able to detect significant changes associated with known radiosonde type changes. Such changes would have a significant impact on long-term trend estimates. Diurnal sampling errors of twice daily radiosonde data are generally within 2%, but can be as much as 10–15% for the once daily soundings. In conclusion, Wang and Zhang (2008) demonstrated that the global GPS PW data are useful for identifying and quantifying three kinds of systematic errors in global radiosonde PW data.

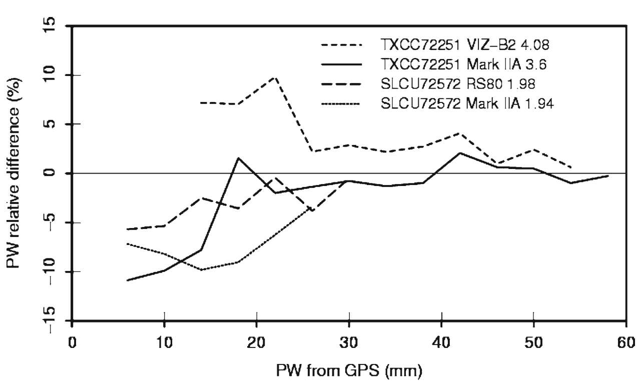

Fig. 2 Median PW relative difference (in %, (IGRA-GPS)/GPS) for all data points in each 4-mm PW bin from GPS for each radiosonde type (VIZ-B2, Mark IIA and RS80H) at Corpus Christi, TX (TXCC72251) and Salt Lake City, UT, USA (SLCU72572). The numbers in the legend are averaged standard deviation (in %) of PW relative differences for each case. The median values with number of data points in each bin less than 40 are removed in the plot

Starting in 2005, US National Weather Service (NWS) introduced the new Lockheed Martin Sippican Mark IIA radiosonde to its network to replace the Vaisala RS80H or VIZ-B2 radiosondes at some stations as part of their Radiosonde Replacement System project. Mark IIA radiosonde uses a capacitance aneroid cell for pressure measurements, a chip thermistor, and a carbon hygristor for humidity measurements. The carbon hygristor used in the Mark IIA is much smaller than the one used in VIZ-B2 (Blackmore, personal communication, 2007). To study the impact of introducing the Mark IIA, the PW comparisons between radiosonde and GPS are made for 2005 and 2006 at two stations (Corpus Christi, Texas and Salt Lake city, UT, USA) where the Mark IIA radiosonde was introduced, and the radiosonde and GPS stations are less than 10 km apart. Figure 2 shows relative PW differences ((IGRA-GPS)/GPS) as a function of PW from GPS for each radiosonde type at two stations. At Corpus Christi, Texas, the VIZ-B2 and Mark IIA were used before and after October 2005, respectively. At Salt Lake City, UT, the Mark IIA was introduced in September 2005. Prior to that the Vaisala RS80H had been used. The Mark IIA shows a dry bias of ∼5–10% in PW at low PWs (less than ∼ 16 mm for Corpus Christi and less than ∼ 25 mm for Salt Lake City), but good agreement with GPS at PWs larger than 16 mm at Corpus Christi (Fig. 2). The VIZ-B2 and RS80H sensors exhibit moist and dry biases, respectively (Fig. 2). Note that Salt Lake City is a high altitude site, with an elevation of 1,290 m, and thus has PW values less than 30 mm all year around. Figure 2 suggests that the Mark IIA radiosonde has a dry bias in dry environments, which is consistent with the finding of large frequency of dry bias instances for relative humidity (RH) less than 30% made by Van Cleve and Klimowski (2007).

The global, 2-hourly GPS PW dataset is also used to evaluate three reanalysis products, namely the NNR, ERA-40 and JRA. The comparisons show that the PW differences are negatively and linearly correlated to the altitude differences between the reanalysis surface level and the GPS stations with correlation coefficients of higher than 0.84 (Fig. 3). This is expected, and was shown by Morland et al. (2006) for the Alpine region. The outliers in the upper-left quarter on left panels of Fig. 3 are primarily from mountainous GPS stations, and the ones in the lower-right quarter are dominated by GPS stations located at the foot of mountains or in the

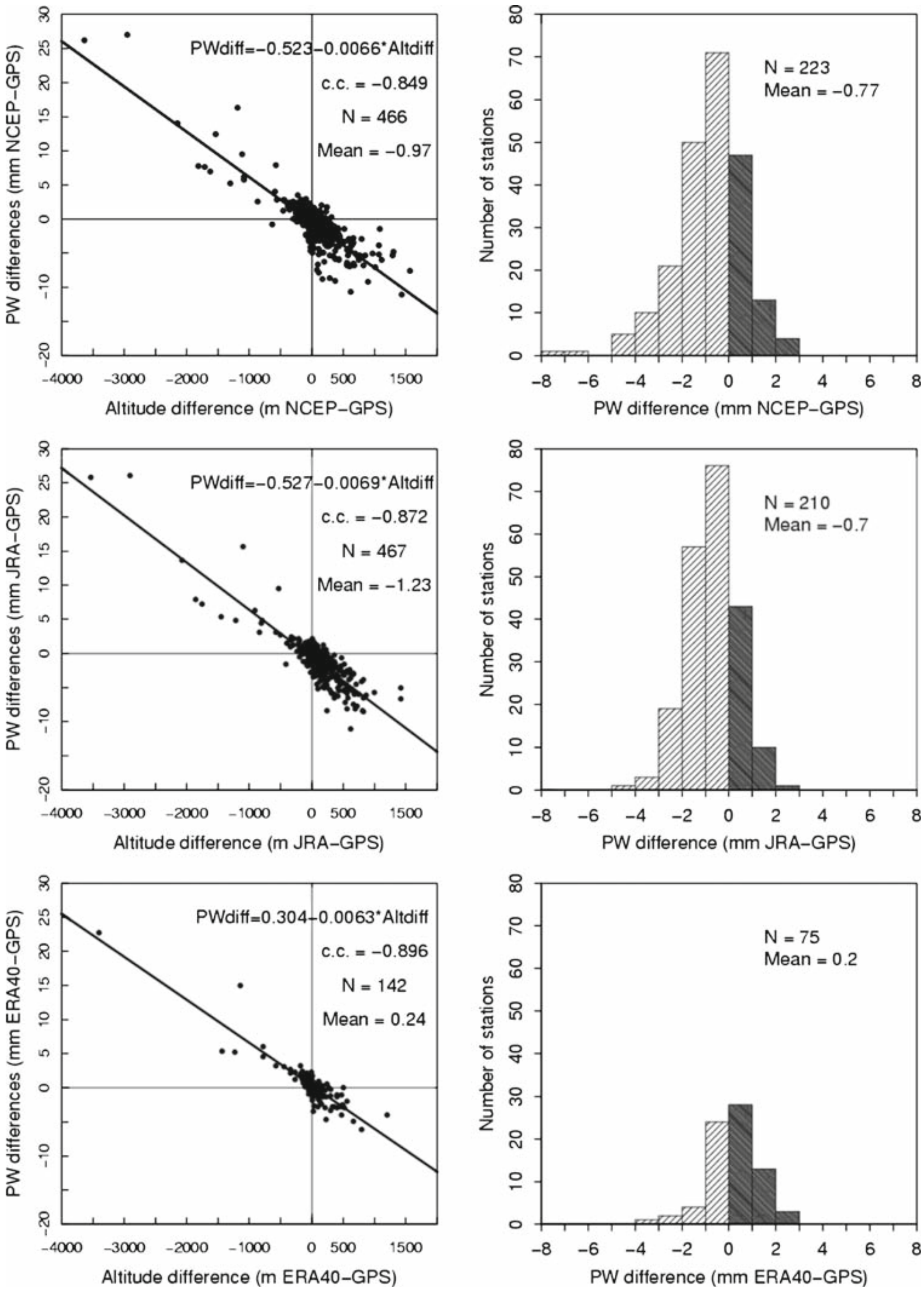

Fig. 3 The left panels show the scatter plots of mean PW differences (in mm) between three reanalysis datasets and the GPS dataset as a function of differences in reanalysis model surface altitude and GPS station elevation. Each *dot* represents one station. The linear regression, correlation coefficient (*c.c.*), number of stations and mean difference are given in the legend. The *right panels* show the histogram of mean PW differences (in mm) at stations with the surface altitude differences less than 100 m

valley of large mountain areas. For stations with the altitude differences less than 100 m that limits the contributions of elevation differences to PW differences, most of stations show drier PWs than the GPS data in NNR and JRA, but slightly wetter PWs in ERA-40 (Fig. 3).

Three GPS stations, Jozefoslaw in Poland, Wu-Han in China and Macquarie Island, are found to have approximately co-located radiosonde stations and have data available for both the GPS and radiosonde data for the complete 9-year period (1998–2006). Monthly mean PW comparisons of radiosonde and the three reanalysis products with the GPS data are shown in Fig. 4. Note that the elevation difference between GPS and radiosonde/reanalysis data is less than 100 m for all three stations, which minimizes the contributions of elevation differences to PW differences. Three main conclusions can be drawn from Fig. 4. Firstly, similar variability in PW differences is generally observed for radiosonde and the three reanalysis products. This is expected because the same radiosonde data are used by all reanalysis models. Secondly, the differences between radiosonde and

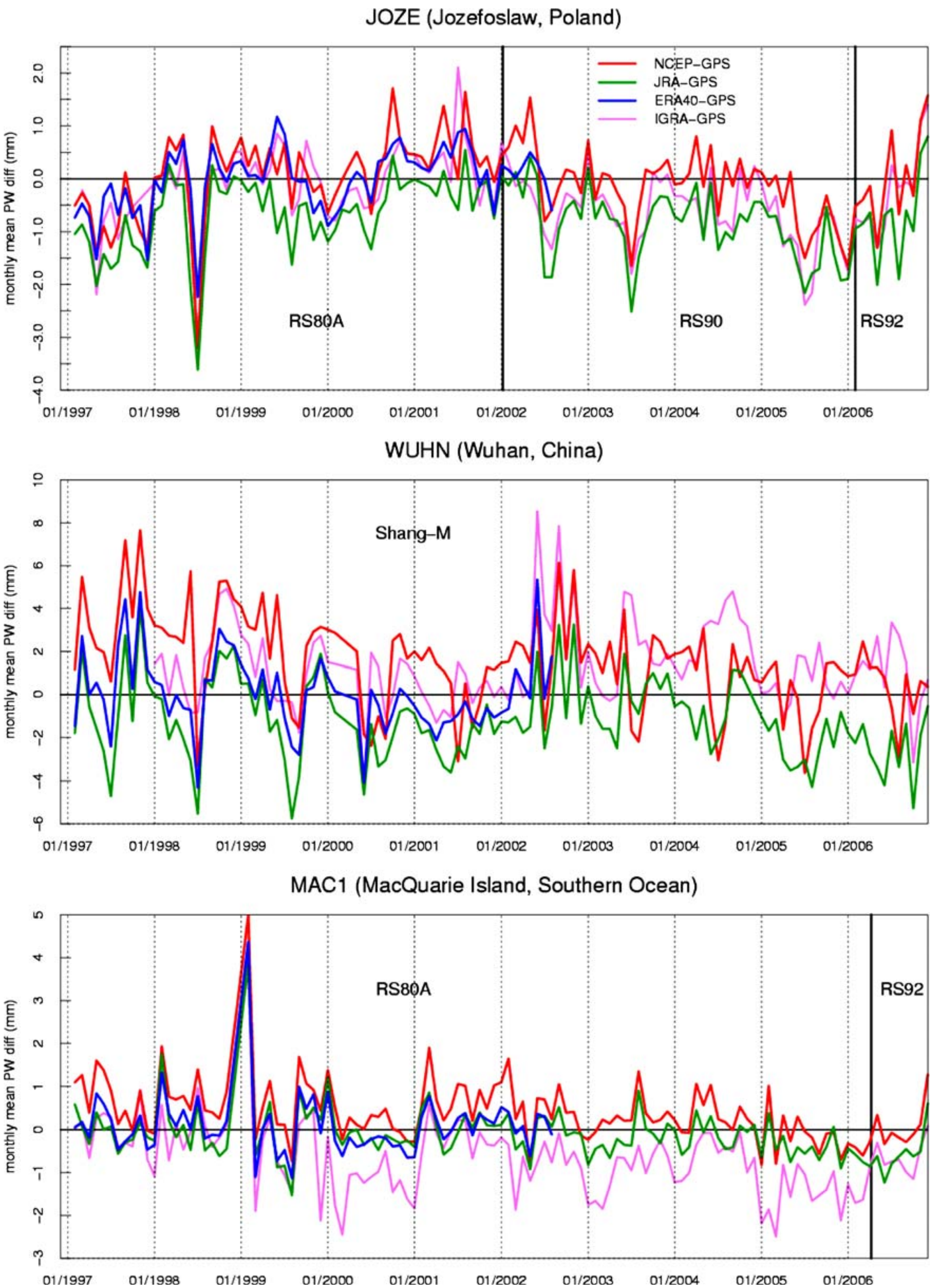

Fig. 4 Monthly mean PW differences (in mm) between the reanalysis or radiosonde (IGRA) data and GPS data from February 1997 to December 2006. The radiosonde types are labeled with *vertical solid lines* denoting the time when the radiosonde type was changed

GPS values indicate known biases in radiosonde data, and switches from one type to another one. At Jozefoslaw, the dry bias in the RS90 data is larger than that in the RS80A and RS92. The Chinese Shang-M radiosonde used at

Wu-Han is characterized by a consistent wet bias due to the slow response of the Goldbeater's skin. At Macquarie Island, a consistent dry bias in the radiosonde data is evident throughout the period. Thirdly, among the three reanalysis products and at all three stations, the JRA is generally the driest one, while the NNR is the wettest one. JRA and ERA-40 agree better with each other than with NNR at Wu-Han and Macquarie Island. The large dry bias in the Vaisala RS90 data at Jozefoslaw is evident in the JRA, but the radiosonde biases at Wu-Han and Macquarie Island are not apparent in the reanalyses.

4 PW diurnal variations

The diurnal cycle is one of the most pronounced variations, but there has been a lack of data with sufficient temporal resolution to study diurnal variations of water vapor. The 2-hourly GPS PW can fill this gap. Global, Northern Hemispheric (NH), and Southern Hemispheric (SH) area-averaged PW diurnal anomalies are shown for annual, DJF (December, January, and February) and JJA (June, July, and August) in Fig. 5. The GPS station data are first gridded to a 2.5° × 2.5° grid box, and then the area-averaged values are calculated. It should be noted that the values in Fig. 5 do not represent true global or hemispheric means because the GPS stations do not fully sample the globe. PW diurnal variations (peak-to-peak amplitudes) account for less than 5% of annual mean PW. Global, NH, and SH annual mean peak-to-peak amplitudes are 0.66, 0.53, and 1.11 mm, respectively, which is an order of magnitude smaller than seasonal variations. For the global and hemispheric averages, PW peaks from noon to late evening. Geographical variations of PW diurnal cycle show that the amplitude is generally smaller at higher latitudes than in the tropics, largest in summer, changes significantly from station to station, and the peak is from noon to mid-night (not shown). Seasonal variations of PW diurnal anomalies along with PW sub-monthly variability are presented for four regions: Europe, southern latitudes (30°–70°S), NH Mountains (NH stations with elevations larger than 500 m), and Darwin (three IGS stations in the area, DARR, DARW, and JAB1) (Fig. 6). The sub-monthly variability is much larger than the diurnal variation. That is not surprising because the sub-monthly variability is mainly a result of weather systems, whereas various competing factors can contribute to the diurnal variation. The sub-monthly variability is strongest in summer in all regions except Darwin, where negligible seasonal variation is found (Fig. 6). Over Europe the PW diurnal cycle is strongest in summer with a peak-to-peak amplitude of ∼ 1.2 mm, but weakest in spring; the local time of the maximum value makes a transition from early evening (∼2000–2200 LST) in summer to late afternoon (∼1600–1800 LST) in autumn and then to

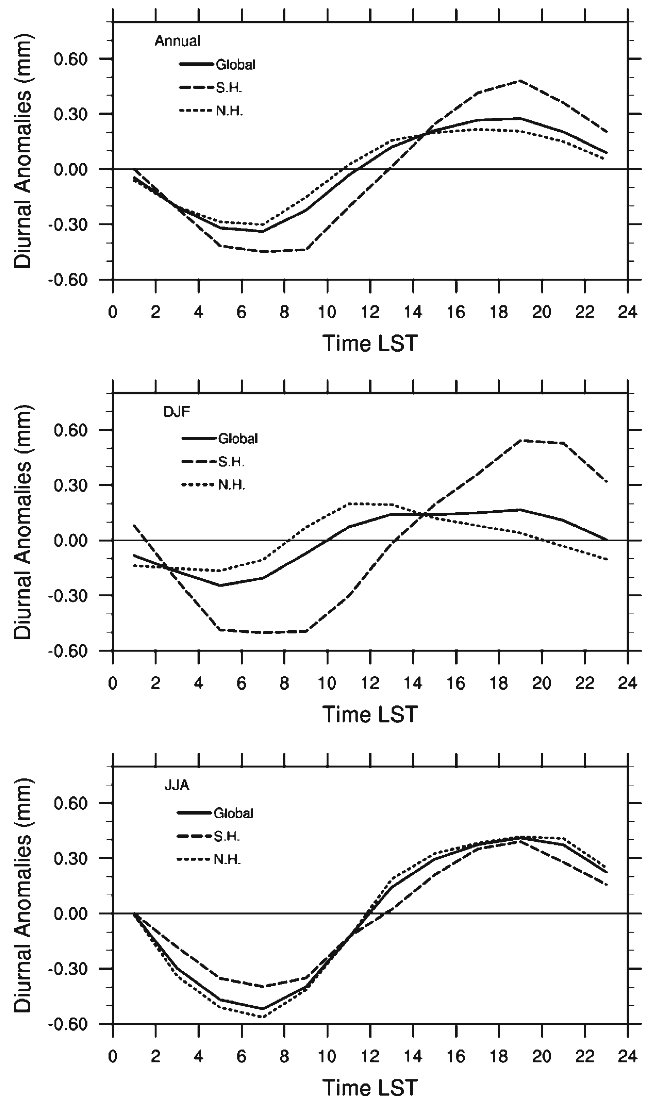

Fig. 5 Global, NH, SH area-averaged PW diurnal anomalies for annual (*upper*), DJF (*middle*) and JJA (*lower*)

before noon (1000–1200 LST) in winter. The PW diurnal cycle in the southern latitudes, NH Mountains, and Darwin have similar phase in the four seasons (time of maximum from late afternoon to early evening) but different amplitudes. The southern latitudes have the smallest diurnal cycle, while the Darwin region has the largest one, with peak-to-peak amplitude greater than 2 mm. Seasonal variations of the PW diurnal cycle are largest in phase over Europe, and largest in amplitude in the mountainous regions and Darwin.

The PW diurnal anomalies and their seasonal variations together with PW's sub-monthly variations over Europe from the three reanalysis products are compared with those from GPS in Fig. 7. The average in Fig. 7 for the reanalysis products is only applied to grid boxes containing GPS stations. The PW diurnal cycle is very weak and poorly represented in amplitude, phase and seasonal variation in the NNR and

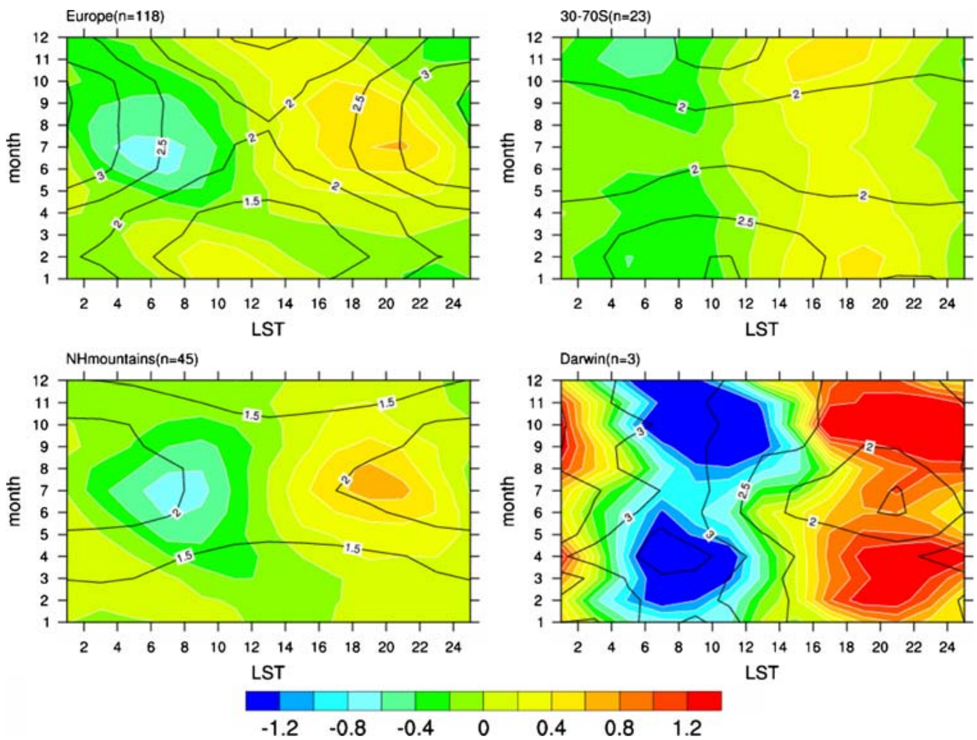

Fig. 6 Seasonal variations of PW diurnal anomalies (in mm, *color*) in four regions. The number of GPS stations in each region is given in the parenthesis in the title. The contours show the PW sub-monthly variability (in mm)

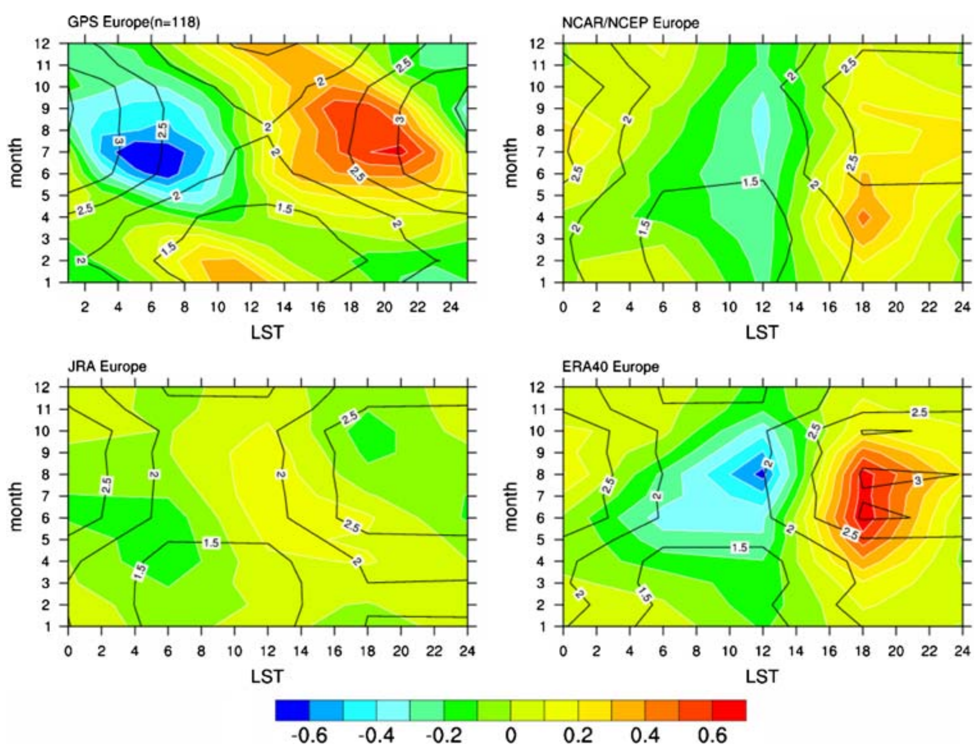

Fig. 7 As in Fig. 6, but for the GPS and three reanalysis datasets over Europe

JRA. ERA-40 shows a peak about 3 h early than the GPS data in summer, and fails to show the phase transition from summer to winter evident in the GPS data. Examination of individual stations reveals that the PW diurnal cycle among stations has similar phases, but different amplitudes for both the GPS data and reanalysis products. All three reanalysis datasets perform well in predicting sub-monthly variability and its seasonal and diurnal changes.

5 Conclusions and future needs

A global, 2-hourly PW dataset has been created using the IGS tropospheric products at about 80–370 stations for the period from 1997 to 2006 and will be continually updated. The dataset can be used for a variety of scientific applications in both climate and weather research. Three climate applications are highlighted in this study: quantifying various types of systematic errors in global radiosonde PW data, evaluating three reanalysis datasets and studying the PW diurnal variations over the globe. This GPS-based PW dataset, created from the existing IGS ZTD products provides a valuable, new source of water vapor data for climate and weather studies. As the GPS data accumulate over time, this PW data set will become increasingly useful for studying long-term water vapor trends. In order to continually update the GPS PW dataset and maintain its high quality, it is essential to sustain high-quality IGS ZTD products. Based on the experience with the IGS ZTD products in this and previous related studies, the following recommendations for improving IGS tropospheric products for climate applications are made.

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

Maintaining long-term stability is very important for the application of the ZTD products to climate studies. For long-term climate applications, the lack of consistency over time in the 2-hourly ZTD products (referred to as the legacy products) is of a particular concern as it results from occasional changes made by individual analysis centers (ACs) in their GPS data handling and their ZTD estimation algorithms (Byun et al. 2005). The quality of the legacy ZTD data is also a concern. Starting from October 2000, the 5-min ZTD data at all IGS sites were also generated using the precise point positioning approach (Byun et al. 2005; Humphreys et al. 2005). The new ZTD 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). It is recommended that the IGS commits to continually deliver the 5-min product. In addition, it is also important to better document the IGS products by: (1) including details on data characteristics and how they were derived, (2) maintaining comprehensive metadata to document any changes in instruments, data processing and other factors, and (3) making all documents available to users.

5.2 To reduce diurnal biases in the ZTD products

An important application of the 2-hourly GPS PW dataset is studying PW diurnal variations, hence the diurnal bias in ZTD should be minimized. Five out of the seven ACs use the mapping function from Niell (1996), which does not include mapping function variations on time scales less than one year. The diurnal mapping function error could potentially introduce errors in PW diurnal variations. The diurnal bias in Tm can directly introduce PW diurnal error. The Bevis Tm and surface temperature (Ts) relationship is commonly used to derive Tm (Bevis et al. 1992). Wang et al. (2005) found that a serious problem in Tm derived from the Bevis relationship 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 and cause 1–2% day-night biases in GPS-derived PW. Therefore, Tm is calculated using the reanalysis data in our analysis method; and caution has to be exercised when using the diurnally invariant Tm–Ts relationship.

5.3 To improve and increase surface meteorology data

Surface meteorology data, especially surface pressure, are required for calculating the dry delay and removing atmospheric pressure loading. Currently there are ~90 IGS stations that provide surface meteorology data. However, surface meteorology data are often very noisy and cannot be used without careful examination and quality control. Besides improving the quality of surface meteorology data, more stations with surface pressure and temperature measurements are also needed, especially with the availability of 5-min ZTD data, since only surface meteorology data can provide 5-min surface pressure data to calculate ZHD. Furthermore, co-located surface meteorology data can be very useful for climate process studies. The collaboration between IGS and national/governmental bodies is necessary to improve and increase surface meteorological data.

5.4 To co-locate with radiosonde stations

The GPS PW dataset is valuable for monitoring the quality of radiosonde humidity data. However, the displacements of GPS and radiosonde stations in space can make the comparisons complicated because of large variability of humidity in both space and time. Wang et al. (2006) provide an example in La Jolla, CA, USA, where the 9-km separation between GPS and radiosonde stations results in PW differences greater than 5 mm. It suggests that one should be very careful about the comparison between radiosonde and GPS PW if the stations are not co-located; and in the future it is very important to co-locate GPS and radiosonde stations. Such co-location is beneficial to both GPS data processing and radiosonde data quality control, and can be achieved through suitable collaboration between IGS and other national and international bodies. Radiosonde data can be used to derive the mapping function for GPS data processing, and the GPS data are very useful for monitoring the quality of radiosonde humidity data both in real-time and for 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 biases in the estimation of global and hemispheric mean values, based on our comparisons with satellite PW datasets (Wang et al. 2007). Therefore, it is recommended to add more IGS stations and integrate other regional GPS networks into the IGS network, such as the integration of the US SuomiNet data into the IGS data, as was done in this study. In addition, incomplete temporal coverage in the IGS ZTD data makes it difficult to calculate monthly, seasonal, or even annual mean values. In future, data gaps should be minimized, and special efforts made to improve the temporal coverage of the IGS ZTD data.

Acknowledgments This work was supported by a NOAA grant (No. NA06OAR4310117). J. Wang would like to acknowledge the support from NCAR T^{II}MES Water System Program. We would like to thank Aiguo Dai (NCAR) for useful comments, Teresa Van Hove (UCAR) for providing SuomiNet data, Imke Durre (NOAA) for providing the IGRA data, Joe Facundo and Bill Blackmore (NWS) for providing the US radiosonde metadata, and Chris Rizos (Australia) for editing the English. The National Center for Atmospheric Research is sponsored by the US National Science Foundation.

References

Beutler G, Rothacher M, Schaer S, Springer TA, Kouba J, Neilan RE (1999) The International GPS Service (IGS): an interdisciplinary service in support of earth sciences. Adv Space Res 23:631–635

Bevis M, Businger S, Herring TA, Rocken C, Anthes R, Ware RH (1992) GPS Meteorology—remote-sensing of atmospheric water-vapor using the global positioning system. J Geophys Res 97(D14):15787–15801

Byun SH, Bar-Serve Y, Gendt G (2005) The new tropospheric product of the International GNSS Service. In: Proceeding of 2005 ION GNSS Conference, Inst Of Navig, Long Beach

CCSP (2005) Temperature trends in the lower atmosphere: steps for understanding and reconciling differences. Synthesis and assessment product 1.1 of US Climate Change Science Program, available on http://www.climatescience.gov/Library/sap/sap1-1/default.htm

Dai A, Wang J, Ware RH, Van Hove T (2002) Diurnal variation in water vapor over North America and its implications for sampling errors in radiosonde humidity. J Geophys Res 107(D10). doi:10.1029/2001JD000642

Deblonde G, Macpherson S, Mireault Y, Heroux P (2005) Evaluation of GPS precipitable water over Canada and the IGS network. J Appl Meteorol 44:153–166

Durre I, Vose RS, Wuertz D B (2006) Overview of the Integrated global radiosonde archive. J Climate 16:53–68

GCOS (2004) Implementation plan for the global observing system for climate in support of the UNFCC. GCOS–92, WMO/TD No. 1219

Hagemann S, Bengtsson L, Gendt G (2003) On the determination of atmospheric water vapor from GPS measurements. J Geophys Res 108(D21). doi:10.1029/2002JD003235

Humphreys TE, Kelley MC, Huber N, Kintner PM Jr (2005) The semidiurnal variation in GPS-derived zenith neutral delay. Geophy Res Lett 32. doi:10.1029/2005GL024207

Morland J, Liniger MA, Kunz H, Balin I, Nyeki S, Matzler C, Kampfer N (2006) Comparison of GPS and ERA40 IWV in the Alpine region, including correction of GPS observations at Jungfraujoch (3584 m). J Geophys Res 111(D04102). doi:10.1029/2005JD006043

Niell AE (1996) Global mapping functions for the atmosphere delay at radio wavelengths. J Geophys Res 101:3227–3246

Trenberth KE, Fasullo J, Smith L (2005) Trends and variability in column-integrated atmospheric water vapor. Clim Dyn 24:741–758

Van Cleve DD, Klimowski BA (2007) Addressing the Sippican Mark IIA radiosonde dry bias at the NOAA/NWS Weather Forecast Office in Flagstaff, AZ, presentation at The National Weather Association's 32nd Annual Meeting, Reno, Nevada, 13–18 October 2007 (Available on http://www.nwas.org/meetings/nwa2007/index.php)

Wang J, Zhang L (2008) Systematic errors in global radiosonde precipitable water data from comparisons with ground-based GPS measurements. J Clim 21:2218–2238

Wang J, Zhang L, Dai A (2005) Global estimates of water-vapor-weighted mean temperature of the atmosphere for GPS applications. J Geophys Res 110(D21101). doi:10.1029/2005JD006215

Wang J, Zhang L, Dai A (2006) A global, 2-hourly atmospheric precipitable water dataset from IGS ground-based GPS measurements: scientific applications and future needs. In: Proceeding of IGS workshop 2006, 8–11, May 2006, Darmstadt, Germany

Wang J, Zhang L, Dai A, Van Hove T, Van Baelen J (2007) A near-global, 2-hourly data set of atmospheric precipitable water dataset from ground-based GPS measurements. J Geophys Res 112(D11107). doi:10.1029/2006JD007529

Ware RH et al (2000) SuomiNet: A real-time national GPS network for atmospheric research and education. Bull Am Meteorol Soc 81:677–694