Precipitable water vapor estimates from homogeneously reprocessed GPS data: An inter-technique comparison in Antarctica

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Abstract

Homogeneously reprocessed GPS data offer the possibility of an accurate, stable and increasingly long-term record of integrated precipitable water vapor (PW), of particular value in data sparse regions. We present such a global reanalysis of GPS data, focusing on 12 Antarctic sites. We show step-wise improvements of GPS Zenith Total Delay (ZTD) estimates upon adoption of each of: (i) absolute antenna phase centre variations, (ii) VMF1 tropospheric mapping functions, and (iii) an accurate model of *a priori* Zenith Hydrostatic Delay (ZHD) from observed surface meteorological data. The cumulative effect of these three additions to the analysis is a systematic decrease in the magnitude of GPS estimates of ZTD, by an average of ~11 mm (~1.8 mm PW). The resultant GPS PW dataset for 2004 shows a mean bias to radiosonde measurements of -0.44 mm. Our conclusion is that, in Antarctica at least, a proportion of the widely observed bias between GPS and radiosonde measurements can be explained by earlier GPS analysis deficiencies.

We also compare our GPS PW measurements with AIRS and MODIS level-2 PW products. The GPS agreements with AIRS and MODIS are comparable. Reanalyzed GPS gives typically larger measurements than AIRS with a mean site bias of 0.89 mm and mean rms of 1.64 mm. By contrast the GPS measurements are typically smaller than those from MODIS, with a mean site bias of -0.35 mm and rms of 1.42 mm. PW

An edited version of this paper was published by AGU. Copyright (2011) American Geophysical Union.
J. Geophys. Res., 116, D04107, doi:10.1029/2010JD013889.

estimates from reprocessed GPS solutions using state-of-the-art models now have greater potential for assimilation into regional or global Numerical Weather Models (NWMs).

1. Introduction

Atmospheric water vapor is a key element of the global hydrological cycle and a major contributor to the natural greenhouse effect. It thus plays a vital role in the Earth's climate system on both global and regional scales, not least due to the now widely accepted 'water vapor feedback' [e.g. *Dessler and Sherwood*, 2009; *Solomon*, 2007]. Long-term, accurate and stable estimates of water vapor are thus required by the climate and meteorological communities. The Global Positioning System (GPS) has long offered the prospect of such a source of point-wise column integrated precipitable water vapor (PW) [e.g. *Bevis et al.*, 1994; *Rocken et al.*, 1995; *Tregoning et al.*, 1998]. Up to 15 years of GPS data are now available, and the global network of GPS tracking stations continues to expand. However, GPS may not yet have fully reached its potential, for example as highlighted by *Haase et al.* [2003] who demonstrate a mean bias of 7 mm of ZTD between GPS and radiosonde records in the Mediterranean region. The principal cause of such typically observed GPS / radiosonde inter-technique differences is often considered to be not GPS-related [e.g. *Wang and Zhang*, 2008], and radiosonde technique and instrument-specific biases are well known and reported in the literature [e.g. *Miloshevich et al.*, 2006; *Vömel et al.*, 2007]. Indeed, *Haase et al.* [2003] used mainly Vaisala RS80-A radiosondes in their study—a capacitive instrument that forms a majority of operational observations in Europe [e.g. *Häberli*, 2006] and elsewhere—that have been shown to exhibit a 'dry bias' of ~1.2 mm in PW (equivalent to ~7 mm in ZTD) [*Wang and Zhang*, 2008 and references therein].

There have, nevertheless, been recent developments in observation-level models which offer the potential for a step change in GPS PW accuracy and precision. Furthermore, most long-term records are heterogeneous in nature due to time-varying GPS analysis strategies and require consistent reanalysis to avoid offsets and other spurious signals. In this paper we examine the effects of (i) homogeneously reprocessing historic GPS data to yield a consistent PW dataset and (ii) applying recent state-of-the-art observation models, which have been shown to have a notable effect on coordinate time series [e.g. *Tregoning and Watson*, 2009]. We do this in the context of one of the most data sparse, but climatically important, regions on Earth: Antarctica.

In Antarctica the spatial distribution and temporal variability of atmospheric water vapor influences precipitation patterns and hence ice-accumulation rates over the continental interior [e.g. *Connolley and King*, 1993], thereby potentially affecting the magnitude of the overall mass balance of the ice sheets. However, there remains a relative scarcity of reliable and calibrated water vapor observation data [e.g. *Monaghan et al.*, 2008], in large part due to the scale and inaccessibility of the region. This shortage of input and verification data for Global Climate Models (GCMs) can result in poorly constrained model outputs. For example, *Monaghan et al.* [2008] suggest that GCMs are consistently overestimating increasing trends in Antarctic water vapor, but they note that there is no long-term observational record available to verify such a hypothesis.

It is noted that the vertically integrated nature of GPS measurements perhaps limits their usefulness for certain aspects of climatic research. In particular, such measurements provide no information on the vertical stratification of water vapour in the climatically important upper troposphere [e.g. *Stocker et al.*, 2001]

Nevertheless, a long-term, accurate and stable water vapor data set for Antarctica would certainly find wide use, e.g. for verification of other measurement techniques, for assessment of trends in climate or meteorological studies, and for assimilation into NWMs. We thus present a reprocessed GPS dataset of PW at locations on the Antarctic continent for 2004, together with an assessment of the current capability of GPS by means of a comparison with other PW datasets. We focus on inhomogeneities in many of the GPS water vapor datasets published to date—particularly the International GNSS Service (IGS) [*Dow et al.*, 2009] ZTD product [*Byun and Bar-Sever*, 2008]—and on a number of the GPS systematic biases that can now be eliminated by reprocessing with the latest models.

2. Background

The IGS were early to recognize the potential capability of GPS to provide useful meteorological observations, and started producing a 2-hourly ZTD product in 1997, which has been used in various meteorological studies over the years (the acronym ZTD is often defined, equivalently, as 'Zenith Tropospheric Delay'; additionally, Zenith Path Delay, ZPD, is often used interchangeably with ZTD). From the IGS ZTD measurements, the Zenith Wet Delay (ZWD) can be obtained by subtracting the Zenith Hydrostatic Delay (ZHD) if pressure data are available. ZWD can then be mapped to PW [e.g. *Bevis et al.*, 1992] based on an estimate of the mean temperature of the atmosphere. Throughout this study, we quantify atmospheric water content using the quantity PW, in units of length. This is defined as the depth of liquid water in a vessel of unit cross-sectional area that would result if the water contained in a vertical column of unit cross-sectional area were condensed. Using PW is convenient since it has units of length, as does the fundamental quantity of ZTD, from which it is derived. The water content of the atmosphere is often alternatively expressed by the numerically equivalent quantity of Integrated Water Vapor (IWV), with units of kg m^{-2}, for example in [*Bevis et al.*, 1992].

An example study that uses the original IGS ZTD product in the Antarctic region is *Vey et al.* [2004], who compared GPS estimates of PW derived from the IGS ZTD product for six Antarctic locations with: (i) observations from the Advanced Microwave Sounding Unit (AMSU-B) instrument, and (ii) the National Centre for Environmental Prediction (NCEP) NWM reanalysis. They observed reasonably high correlations between the three datasets (of order 0.8), although they noted inter-technique, site-dependent biases that ranged from -1.7 mm to +1.2 mm of PW for the three way comparison (or equivalently, ~-10 mm to ~+7 mm ZWD). This magnitude of bias is comparable to results from studies in other geographical locations. For example, *Glowacki et al.* [2006] show GPS to be consistently positively biased relative to radiosonde measurements (with magnitudes ranging from +0.5 mm to +2.2 mm PW, or equivalently +3 mm to +13 mm ZWD) at a wide range of latitudes in the Australian region, including Antarctica. Similarly, in a Europe based study, *Bock et al.* [2005] found both radiosonde and European Centre for Medium-Range Weather Forecasts (ECMWF) NWM PW estimates to be negatively biased compared to GPS measurements, by 5.5% and 4.5% respectively. Both *Glowacki et al.* [2006] and *Bock* *et al.* [2005] used Vaisala RS80-A radiosondes, which exhibit a dry bias of up to ~1.2 mm PW, as previously noted [*Wang and Zhang*, 2008].

Over recent years, GPS models and processing strategies have advanced substantially. In particular, the development of calibrated absolute antenna phase-center variations and offsets (PCVs and PCOs, henceforth referred to as 'absolute PCVs') for both transmitters and receivers has been shown to result in a significant improvement in the precision and accuracy of GPS derived ellipsoidal heights [e.g. *Steigenberger et al.*, 2006], and the highly correlated ZTD estimates [e.g. *Vey et al.*, 2002]. The systematic effect of including absolute PCVs is due to the resulting improvement in scale (and its rate of change) of the GPS solutions [e.g. *Ge et al.*, 2005], since the PCVs are themselves estimated as part of global solutions in which the scale is fixed to that of ITRF2000 [*Schmid et al.*, 2005]. In the latter study on the impact of absolute PCVs, a reduction in the inter-technique bias between ZTDs estimated from GPS and Very Long Baseline Interferometry (VLBI) was demonstrated.

Improved tropospheric mapping functions (MFs), which allow tropospheric slant delays along each satellite-receiver path to be mapped to the zenith have been developed. One of these is the Vienna Mapping Function 1 (VMF1) [*Boehm et al.*, 2006] which is based on ray tracing of the ECMWF NWM. The VMF1 MFs are considered to be the best currently available and substantial differences in derived coordinates [e.g. *Tregoning and Watson*, 2009] and ZTDs compared with earlier analyses (e.g. those using the older Niell mapping function [*Niell*, 1996]) have been reported. Furthermore, the use of an accurate *a priori* ZHD, e.g. derived from observed surface meteorological data or from ECMWF NWM data, has been shown to be important in the accurate determination of station height [*Tregoning and*

Herring, 2006] and also, due to the well established correlation with station height, estimated ZTDs. *Tregoning and Herring* [2006] note this to be of particular importance for relatively high latitude regions such as Antarctica, due to the higher proportion of low elevation angle observations.

The original IGS ZTD product (the ‘legacy product’) used by *Vey et al.* [2004], was produced from 1997 onwards from a combination of estimates of ZTD from several IGS Analysis Centers (ACs). This product was increasingly recognized by the community to be unsatisfactory, due to its inhomogeneous nature caused by the varying processing strategies and the different input data used by the ACs and changes in these choices over time [e.g. *Byun and Bar-Sever*, 2008]. In 2003, therefore, an effort was made to improve the quality and consistency of the product by replacing it with a newer IGS product, produced by the Jet Propulsion Laboratory (JPL) alone, using IGS final orbits and the precise point positioning (PPP) capability of their GIPSY software. Byun and Bar-Sever [2008] give an overview of the ‘legacy’ and ‘new’ (current) IGS ZTD products, including a discussion of the deficiencies of the former, and some remaining limitations of the latter.

The benefits of reanalyzing the complete archive of GPS observation data with consistent use of up-to-date models are now widely recognized and demonstrated within the GPS geodetic community [e.g. *Steigenberger et al.*, 2006]. For studies whose aim is to investigate secular trends, e.g. the identification of climatic trends in a GPS derived water vapor dataset, it is essential that GPS measurements are obtained from consistently analyzed GPS orbits to give the best long-term temporal stability and homogeneity, as well as minimizing known GPS systematic errors. Despite the above stated shortcomings in the legacy, and to a lesser extent, in the current, IGS products, both have been widely used in recent studies. The legacy IGS product has been employed in global climate studies [e.g. *Wang et al.*, 2007; *Wang and Zhang*, 2009] and has been used as a 'truth' dataset to assess the long-term stability of radiosonde-derived humidity measurements [*Wang and Zhang*, 2008]. Recent regional meteorological studies [e.g. *Nilsson and Elgered*, 2008] have also used GPS analysis strategies that do not include, to name one significant 'new' model, the absolute PCVs. ZTD and PW measurements from homogeneously reprocessed GPS data have been presented by *Steigenberger et al.* [2007] and *Vey et al.* [2009] respectively. However, the reanalysis used in these studies, whilst homogeneous, is limited by the use of the Isobaric Mapping Function (IMF) [*Niell*, 2000; *Vey et al.*, 2006] and the basic Saastamoinen model [*Saastamoinen*, 1972] and use of a standard atmosphere for the *a priori* ZHD.

In this paper, therefore, we extend the work of *Vey et al.* [2009] to include modeled *a priori* ZHD from observed surface meteorological data, as well as an atmospheric loading (ATML) model. We initially demonstrate the systematic effect of four of the recent models in turn—namely absolute PCVs, the VMF1 MF, accurate *a priori* ZHDs, and ATML—on the absolute values of GPS derived ZTDs, and then investigate the effect of these models on biases relative to the IGS ZTD product. We then derive PW, and present a comparison of these GPS measurements with three independent datasets for Antarctica: *in situ* radiosonde observations and remotely sensed data from two instruments aboard NASA's Aqua satellite, AIRS and MODIS.

3. Datasets

3.1. GPS observation data

Homogeneous reprocessing of GPS data requires global data sets from which the satellite orbits and Earth orientation parameters may be estimated. We used 60 site GPS networks that incorporated 12 Antarctic sites (our area of interest) plus 48 additional 'global' GPS sites from the IGS network, selected to provide a good overall global distribution of sites, whilst simultaneously ensuring reasonable day-to-day continuity of the network. A typical daily 60-site network from 2004, that from 1 July, is seen in Figure 1. There are day-to-day variations in site availability, but we retained similar geometry throughout the period.

Locations of the 12 continuously recording GPS receivers on the Antarctic continent used are indicated in **Error! Reference source not found.**~~Figure 2~~ and are summarized in Table 1, ordered by increasing station longitude from site SYOG. We use a full year of measurements from 2004 as the dataset for this study; this is a convenient year for which all four comparison datasets used are available.

Site AMUN, at the South Pole, is located on an ice sheet which is moving with a horizontal velocity of ~10 m yr^{-1}, or ~2.7 cm within each 24-hour processing session, which if unaccounted for would likely result in biased orbits. Therefore a procedure similar to that described by *King et al.* [2000] was used to modify the observation data: the long-term site velocity was derived from a standard GPS PPP analysis of the full time series and subtracted from the daily GPS data at the observation level.

3.2. Surface meteorological observation data

Observed surface temperature and pressure data is required for (i) an accurate *a priori* ZHD model [*Tregoning and Herring*, 2006] for use in the GPS analysis itself, and (ii) for the determination of the dimensionless constant for the conversion of GPS derived ZWD to PW [e.g. *Bevis et al.*, 1994]. For the Antarctic sites, meteorological data were obtained (from http://www.antarctica.ac.uk/met/metlog/, accessed April 2007), as summarized in Table 1. Basic filtering was undertaken to remove obviously spurious points. The meteorological sensors are typically located less than a few hundred meters horizontally, and a few tens of meters vertically, from the GPS antennas. The observed pressure is corrected for the vertical height offset, Δh, using the 'barometric formula' [*Mario et al.*, 1997], which models how the pressure varies with height. The observed surface temperature is likewise mapped to the GPS antenna location using a standard adiabatic atmospheric lapse rate of 0.0065 ºC m^{-1}. The Antarctic temperature and pressure data are typically provided every 3 hours, except for the South Pole which is at 6-hourly intervals. The data were linearly interpolated to the 2-hourly interval used in the GPS ZTD estimation.

Where no observed pressure data are readily available to compute *a priori* ZHD, an alternative 'accurate' model is to derive *a priori* estimates of ZHD from the pressure field of a NWM, such as ECMWF [e.g. *Boehm et al.*, 2006]. For the global (i.e., the non-Antarctic) sites, where we do not have observed pressure data, we use these ECMWF NWM-derived *a priori* ZHDs. This can be considered sufficient, since we do not consider PW at those sites in this study. We briefly consider the magnitude of the differences in ZTD measurements that result from these two alternative methods of obtaining 'accurate' *a priori* ZHD information, in section 4.3.

3.3. Radiosonde

The majority of radiosonde instruments in use in Antarctica during the study period of 2004 were the Vaisala RS80-A model (e.g. CAS1, MAW1 and DAV1). The Vaisala

RS90 model was used at DUM1. The Vaisala RS80 is known to suffer from a dry bias in its humidity measurements, of 1.2 mm, or around 5%; radiosonde biases are discussed widely in e.g. the global GPS based comparative study of *Wang et al.* [2007] and the Antarctic study of *Gettelman et al.* [2006]. The first of these concluded that a mean global PW dry bias of 1.08 mm in the radiosonde measurements relative to GPS is due primarily to these dry biases in the Vaisala instrumentation. It is noted, however, that not all radiosonde types exhibit dry biases. *Wang and Zhang* [2008] worked with a comprehensive world-wide dataset of stations consisting mostly of capacitive sensors (128 out of 169 stations), of which most (103 out of 128) exhibited a dry bias. However, carbon hygristors and Goldbeater's skins typically exhibited a moist bias. Most of the sensors were also observed to show a day / night differential behaviour, with a dry bias in daytime due to the solar radiative heating. At cold temperatures most sensors are also known to exhibit large time lag errors. These radiosonde biases and errors, together with work carried out within the radiosonde community to develop correction factors to account for them, are discussed in great detail in the literature [e.g. *Miloshevich et al.*, 2006; *Rowe et al.*, 2008; *Turner et al.*, 2003]. For the purposes of this study that is primarily concerned with improvements in the absolute accuracy of GPS measurements, we note the existence of such radiosonde error sources, and their likely contribution to observed inter-technique biases, particularly due to the cold temperatures in Antarctica. We do not attempt to apply correction factors to the limited number of radiosonde datasets available for the comparison in Antarctica.

Radiosonde data were obtained for the following Antarctic sites: SYOG, MAW1, DAV1, CAS1, DUM1, MCM4 and AMUN. The sondes are generally launched twice daily at 0h00 and 12h00 UTC. A ray-tracing program that computes ZWD from wet and dry refractivity formulae (developed by J. L. Davis, and modified by T. A. Herring and A. E. Niell, and based upon expressions derived by *Davis et al.* [1985]) was used to ray trace through the vertical radiosonde profiles. The sum of ZWD and ZHD gives the radiosonde derived ZTD, for direct comparison with our GPS estimated ZTDs.

For the PW inter-technique comparison (section 5), the radiosonde ZWD measurements were mapped to PW using the same method that is used to map GPS estimates of ZWD to PW [e.g. *Bevis et al.*, 1994]. ZTD is multiplied by a dimensionless constant (with a value of approximately 0.16) that is dependent on the mean atmospheric temperature. This location-specific mean temperature, was estimated from the previously described observed surface temperature measurements, using a global linear regression formula, as described by *Bevis et al.* [1994].

3.4. AIRS instrument

The AIRS instrument is a cross-track scanning instrument aboard NASA’s Aqua and Terra satellite platforms, that measures radiation emitted from the Earth in the visible, infrared (IR), near infrared (NIR) and microwave spectral regions. Column integrated water vapor measurements are produced operationally from AIRS data by NASA. The stated accuracy specification for the absolute AIRS total water vapor product is 5% [*Fetzer et al.*, 2003]. The AIRS water vapor product has been validated in a number of studies, though most validation has been for mid-latitude regions [e.g. *Rama Varma Raja et al.*, 2008]. Using GPS measurements of PW over the USA as a comparative dataset, they note 'excellent' GPS / AIRS agreement, with PW biases ranging from 0.5 mm to 1.5 mm, rms differences of 4.0 mm or less, and monthly correlation coefficients ranging from 0.91 to 0.98. They conclude that, for mid-latitudes at least, the absolute values of AIRS derived total water vapor are dry biased in moist atmospheres (PW > 40 mm) and wet biased in dry atmospheres (PW < 10 mm). Importantly, comparison of AIRS data with GPS or radiosonde PW has not yet been reported for Antarctica.

Here, the ‘totH20Std’ field was extracted from the level-2 ‘AIRX2RET’, version 005 AIRS data product. The horizontal resolution of this AIRS product is 50 km. Daytime AIRS observations within ±0.75° longitude and ±0.25° latitude of the GPS sites were retained; these data were then filtered using Quality Assurance (QA) flags, as detailed in the AIRS QA plan [*Olsen*, 2007].

3.5. MODIS instrument

The MODIS instrument, also aboard NASA’s Aqua and Terra satellites, makes measurements in 36 spectral bands ranging in wavelength from 0.4 μm to 14.4 μm (i.e., largely IR) of which 29 bands record at a spatial resolution of 1 km. Five NIR channels, located in the 0.94 μm water vapor absorption range, are designed for the remote sensing of water vapor. Since the NIR total column water vapor product is derived from attenuation of reflected solar light from the surface, it is available in the daytime only. PW from NIR channels can also be retrieved over clouds. The level-2 MODIS product ‘MYD05_L2’ (collection 005) was used. The ‘NIR water vapor’ field was extracted, and filtered using the cloud mask and QA flags. Observations flagged with 95% confidence of being cloud free are used, the same approach as adopted by *Li et al.* [2003]. Each single MODIS PW measurement is averaged from up to 30 observations. As with AIRS, there is typically a measurement every 1-2 days at Antarctic locations in the austral summer months.

Typical errors in the level 2, 1 km gridded NIR MODIS water vapor product are of the order 5-10% [*Gao and Kaufman*, 2003]. They estimated errors in column water vapor retrievals over snow and ice covered surfaces of 3.9%. These quoted errors are possibly conservative, however, since they correspond to instrument specifications or simulations. Studies that have made use of MODIS data include those of *Li et al.* [2003], who observe that MODIS NIR measurements appear to overestimate PW compared to both radiosonde and GPS in Germany, and *Liu et al.* [2006], who note rms differences to GPS PW of 1.68 mm and 1.9 mm, for locations on the Tibetan Plateau.

The official MODIS documentation (accessed in August 2007 from: http://modis-atmos.gsfc.nasa.gov/MOD05_L2/qa.html) states that "additional validation needs to be done for retrievals over snow and ice-covered surfaces" and that "no conclusion has yet been reached on the accuracy of MODIS measurements over such surfaces, although all seasonal variations seem to be realistic with no obvious error in the NIR derived water vapor."

4. GPS analysis and sensitivity of ZTD to model selection

4.1. GPS data analysis strategy

We use data from 2004.0-2005.0 here, due to the chosen satellite datasets used in the inter-technique comparison being readily available for this year. The GAMIT 10.35 software [*Herring et al.*, 2006] was used to process the daily 60-site global GPS networks. Site coordinates were estimated on a daily basis, with the majority of the estimated site coordinates constrained very loosely to their ITRF2005 values at the level of 100 m in each component direction. Nine of the global IGS sites were moderately constrained to their ITRF2005 coordinates and linear velocities, with *a* *priori* sigmas of 0.02 m and 0.05 m in the horizontal and vertical component directions respectively. The resulting daily solutions were thus an approximate realization of ITRF2005. The other parameters estimated included orbital parameters, Earth orientation parameters (EOPs) and horizontal tropospheric gradients. ZTDs were estimated at 2-hourly intervals as random walk parameters, with a variation of 0.02 m hr$^{-1/2}$ and a correlation time of 100 hours.

We are particularly interested in the systematic effects of incorporating four models into the GAMIT processing strategy:

- Absolute PCVs, for both transmitters and receivers, from ‘antex’ file IGS05_1421.atx [*Schmid et al.*, 2005]. It is noted that DAV1, MAW1 have no calibration of the radome. Additonally, GAMIT excludes observations below 10 degrees for antenna / radome combinations that are uncalibrated.
- VMF1 wet and hydrostatic MFs [*Boehm et al.*, 2006].
- Accurate *A priori* ZHD, computed from observed surface meteorological observations [*Tregoning and Herring*, 2006].
- ATML deformations: 'tidal' and 'nontidal' ATML deformations, applied at the observation level, as detailed by *Tregoning and Watson* [2009]. In summary, the 'nontidal' component of ATML consisted of the convolved National Centre for Environment Prediction (NCEP) reanalysis pressure values, as originally described by *Tregoning and Van Dam* [2005], filtered with a low-pass filter to remove power at sub-daily frequencies. The 'tidal' component of ATML (i.e., deformation at S1 and S2 tidal frequencies) was accounted for using the gridded model of *Ponte and Ray* [2002].

The remainder of our GAMIT processing strategy can be summarized as:

- Elevation cut off angles of 10 and 7.5 degrees were used for Antarctic and global stations respectively. The higher value was considered optimal for high latitude sites when using the VMF1 MF, based on the trade-off between improved geometric accuracy and increased uncertainty for low elevation observations.
- Ocean tide loading (OTL) displacements for the Antarctic sites were modelled using the TPXO6.2 numerical ocean tide model [*Egbert and Erofeeva*, 2002], corrected to be in the centre of mass (CM) frame. This is currently considered the best model for the region [e.g. *King et al.*, 2005; *Thomas et al.*, 2008]. The FES2004 model [*Lyard et al.*, 2006] similarly corrected, as recommended in the unratified updates to the IERS 2003 Conventions, was used at the remaining global sites.
- Carrier phase ambiguities were fixed.

4.2. Replication of IGS ZTD product with GAMIT strategy

The current IGS ZTD product is taken as the starting point for a comparison to investigate the effects of the new GPS models. This product has been generated using a PPP strategy, from IGS orbits, in which the VMF1 MF and accurate *a priori* ZHD model have not been used, and in which absolute PCVs were introduced for data from 2006 onwards. The PPP strategy used by JPL to produce the product is summarized in the left hand column of Table 2. In using GAMIT, we are using a different software package and estimation strategy (double differenced observations in a global network solution) compared with the GIPSY package and PPP strategy used by JPL. Initially therefore, it was necessary to create a 'base' product equivalent to the IGS product, to which the ‘new’ models could then be added to assess their individual effects. This ‘base’ strategy is summarized in the central column of Table 2.

The blue lines in Figure 3 show the ZTD difference between the IGS product and the ‘base’ (i.e. IGS product minus ‘base’) for the 7 sites where the IGS product is available (SYOG, MAW1, DAV1, CAS1, MCM4, OHI2, VESL), illustrating that our ‘base’ strategy is generally successful in replicating the IGS product. Table 3 confirms this, showing that the bias between the IGS ZTD product and our ‘base’ ZTD is typically in the range of ~-1 mm to ~1 mm of ZTD, with a mean of -0.49 mm. There is a relatively larger bias at VESL, of -3.17 mm. The close agreement between the ‘base’ run and the IGS product gives us confidence that the effects of our subsequent addition of models to the ‘base’ solution will be representative of differences to the IGS product. The fact that there is some difference between the IGS product and our 'base', e.g. at VESL, is unimportant for this test into the systematic effects of the models on ZTD, compared with the benefit of complete self-consistency between our solutions.

4.3. Impact of alternative models on ZTD

We test the sensitivity of the ZTDs to different observation models by performing four additional globally reprocessed solutions for 2004, using the models mentioned in section 4.1. The model ‘variant’ solutions are thus: (i) ‘Base + absolute PCVs’ (ii) ‘Base + absolute PCVs + VMF1’ (iii) ‘Base + absolute PCVs + VMF1 + *a priori* ZHD’ (iv) ‘Base + absolute PCVs + VMF1 + *a priori* ZHD + ATML’. The differences in mm of ZTD between each solution and the ‘base’ solution (i.e. ‘variant’ minus ‘base’) are plotted in Figure 3 for each of the 12 sites. The difference of the radiosonde from the ‘base’ run is also plotted for the 7 sites where these measurements exist (SYOG, MAW1, DAV1, CAS1, DUM1, MCM4 and AMUN).

We are primarily concerned with absolute accuracy of GPS, and the magnitudes of the systematic effects of introducing each of the four models are summarized in Table 3. The addition of the ATML model (run (iv)) results in a very small systematic effect (mean biases of the order of 0.05 mm of ZTD). The black line that represents this model run does not show up differently from the previous 'variant' (run (iii) in magenta) in Figure 3. Whilst ATML is observed to have negligible effect on the mean ZTD, it is nevertheless considered an important model to include, especially if higher frequency variability in ZTD is to be captured by the GPS time series.

The remainder of the discussion in this section focuses on the first three model ‘variant' solutions. Introducing each of these models (absolute PCVs, VMF1 and an accurate *a priori* ZHD) to the analysis results in a systematic ‘drying’ of the ZTD measurements relative to the ‘base’ solutions at all Antarctic locations. The bias between the ‘full’ model run and the ‘base’, averaged across all sites for the whole year, is -10.76 mm (i.e., ‘full’ minus ‘base’), corresponding to approximately -1.8 mm of PW. By way of comparison, the typical maximum annual PW in East Antarctica is 6 mm. The overall mean offset between the ‘full’ and ‘base’ runs of -10.76 mm of ZTD can be apportioned between the three individual models as: Absolute PCVs -6.25 mm; VMF1 -2.6 mm; and *a priori* ZHD -1.91 mm. The switch to absolute PCVs thus has the biggest systematic effect in Antarctica, but the other two models combined result in a systematic reduction of almost comparable magnitude.

The effect of the introduction of absolute PCVs on estimated ZTDs is consistent with that reported by *Schmid et al.* [2005]. The findings are also in good agreement with observations made by *Byun and Bar-Sever* [2008]. For a 6 month test period, they found switching from relative to absolute PCVs results in a globally uniform systematic change in estimated ZTDs of between -5 and -7 mm.

Unlike the switch to PCVs, the systematic effect resulting from the introduction of VMF1 is observed to have greater temporal variation. Due to the latitudinal dependence of the VMF1 MF [*Boehm et al.*, 2006], there is also expected to be a greater latitudinal variation in the VMF1 bias, although this is not confirmed here, due to the relatively high latitudes of the study sites.

The effect of introducing an accurate *a priori* ZHD model is, in Antarctica, spatially and temporally reasonably uniform, although the magnitude of the reduction in ZTD is notably larger at AMUN. This is unsurprising, given the high elevation of the South Pole (~2800 mASL) in the continental interior, and the fact that the *a priori* ZHD in the ‘base’ strategy is derived form a standard (constant) atmospheric sea level pressure of 1013.25 hPa, with a simple adjustment for height [*Tregoning and Herring*, 2006]. The accurate *a priori* ZHD used in the model 'variant' runs (and the for final PW analysis) was computed from the observed surface observation meteorological data for Antarctic sites. However, an additional test was undertaken to investigate the effect of using the alternative, ECMWF derived a *priori* ZHD. For our Antarctic sites, switching to this alternative ‘accurate’ model resulted in a systematic reduction in mean ZTD of -0.21 mm (i.e., using ECMWF derived *a priori* ZHD gives ZTD that are, on average, an additional 0.21 mm 'drier', on top of the 1.91 mm reduction observed from introducing our preferred *a priori* ZHD model).

Since the radiosonde provides the traditional meteorological observation dataset, it is of interest to consider the effect of introducing the currently accepted ‘best’ GPS models on the GPS / radiosonde inter-technique biases. In assessing the inter-technique biases, radiosonde is not in any way assumed to be closer to the 'truth' than GPS, and is recognized as having its own set of systematic errors as described in section 3.3. At six of the seven sites with radiosonde data, the radiosonde measurements are systematically drier than our 'base' (‘legacy’) solution. The exception is SYOG, where the ‘base’ GPS ZTD measurements are already ‘drier’ than the radiosonde measurements, prior to the systematic drying effect of the additional GPS models. It is unknown if the anomalous behavior at SYOG originates predominantly from the GPS or radiosonde record. From Figure 3, it can be clearly seen that at three of the six remaining sites (AMUN, CAS1 and DAV1) the addition of the three models ‘closes the gap’ to the radiosonde measurements. At DUM1 and MCM4, the radiosonde differences compared with the ‘base’ GPS ZTD are noisy, but the radiosonde measurements are approximately halfway between the ‘base’ and final model runs, i.e. our ‘best’ GPS estimates of ZTD are now 'drier' than radiosonde at these sites. This is also the case, to a lesser degree, at MAW1. In summary, the effect of the model additions is that the final GPS measurements are either close to, or drier than the radiosonde measurements at all seven sites.

For the remainder of the paper we discuss PW measurements (as opposed to ZTDs), quantitatively assessing the agreement of our GPS PW dataset with the radiosonde record, and two other satellite datasets. The PW dataset is derived from the final ZTD 'model variant' above (i.e. ‘base+abs PCV+VMF1+*a priori* ZHD+ATML’); the GPS analysis strategy is summarized in the right hand column of Table 2. The 2-hourly estimated ZTDs were converted to PW by subtracting the ZHD, and mapping the resulting ZWD to PW using the same conversion as carried out on the radiosonde derived measurements of ZTD, according to *Bevis et al.* [1994], and described in section 3.3~~3.3~~.

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5. PW Results

5.1. Inter-technique comparison of Antarctic PW

Our GPS PW measurements are chosen as the basis against which other techniques are compared, since it is the common data set and has the most continuous coverage.

The GPS PWs were linearly interpolated to the measurement epochs of the relevant comparative data set, for epochs bounded by GPS observations no more than 4 hours apart. Epochs without such GPS PW estimates were not compared. Figures 4 and 5 show the absolute PW measurements from the four techniques for each of the 12 Antarctic sites. **Error! Reference source not found.**~~Figure 6~~ and 7 show the difference in PW between each of the three comparative datasets compared to GPS; in these figures, positive values indicate the measurement to be 'wetter' than GPS.

From Figures 4 and 5 it is observed that all techniques capture a strong annual signal in PW at all sites, with minimum and maximum PW occurring approximately at the austral winter and summer solstices respectively. The East Antarctic coastal locations are drier than the Antarctic Peninsula; the dynamic range in PW is appreciably larger in West Antarctica. The South Pole (AMUN), high on the East Antarctic ice-sheet, is as expected extremely dry, with an annual maximum of ~2 mm PW.

5.1.1 GPS / Radiosonde comparison

For the remainder of the paper, when we discuss inter-technique differences by referring to e.g. the GPS / radiosonde bias, we mean the difference 'GPS minus radiosonde'. Scatter plots of GPS against radiosonde PW can be seen in Figure 8 with fitted linear regression lines. The fit statistics are summarized in Table 4.

The GPS and radiosonde PW show a high level of agreement, with inter-technique biases typically at the sub-millimeter level, and correlation coefficients of ~0.9 or greater. The slope of the regression line for all sites is close to, although generally slightly greater than, unity. Relative to the radiosonde measurements, GPS measurements thus show slight increasing bias to PW with increasing water vapor content.

The GPS / radiosonde statistics compare favorably with previous GPS / radiosonde comparative studies in other regions [e.g. *Li et al.*, 2003] and in Antarctica [e.g. *Vey et al.* 2004]. For example, the East Antarctic sites DAV1 and CAS1, and also MCM4, show a high level of agreement, with small mean biases in PW of +0.29 mm (~7.1% of mean GPS PW), +0.25 mm (5%) and -0.15 mm (5.6%) respectively. As noted for the ZTD measurements, at SYOG, and to a lesser extent at sites MAW1 and DUM1, our reanalyzed GPS measurements of PW are drier than the radiosonde measurements: GPS / radiosonde PW biases at these sites are -2.28 mm (91% of mean GPS PW), -0.58 mm (23.5%) and -0.71 mm (17.5%) respectively. The large, and unexplained, GPS / radiosonde bias at SYOG is temporally uniform throughout the year. The GPS / radiosonde rms differences are as follows: 0.84 mm (20.5% of mean GPS PW), 1.6 mm (39%), 0.64 mm (12.8%) 0.79 mm (29.6%) and 0.99 mm (40.1%) for sites DAV1, DUM1, CAS1, MCM4, MAW1 respectively.

Finally, at AMUN, the GPS / radiosonde comparison shows a small bias of +0.08 mm; this represents ~4% of the maximum annual PW at this dry location. It is unfortunate that there is no co-located radiosonde data available to validate GPS measurements for the slightly more humid and meteorologically more variable, Antarctic Peninsula.

5.1.2 GPS / AIRS comparison

Scatter plots of the GPS / AIRS comparison and linear regression lines of best fit for the 12 Antarctic stations are found in **Error! Reference source not found.**~~Figure 9~~, with summary statistics in Table 4.

The GPS and AIRS comparison shows a mean correlation coefficient of 0.73, a rms difference of 1.64 mm, and a mean GPS / AIRS bias of +0.89 mm PW. At every site, with the exception of MAW1, the mean AIRS PW is ‘drier’ than GPS. The slopes of the regression lines, with the exception of site AMUN, range from 0.83 to 1.25. The observed GPS and AIRS agreement compares favorably with e.g. *Rama Varma Raja et al.* [2008], who demonstrate biases of between 0.5 mm to 1.5 mm, and rms differences of up to 4.0 mm. AIRS does not, however, show quite the same, consistent level of agreement with GPS that is seen in the GPS / radiosonde comparison.

The rms differences are at the sub-millimeter level for sites MCM4 (0.82 mm PW, 25.5% GPS PW) and BELG (0.82 mm, 29.4%), otherwise they are generally notably larger than in the corresponding GPS / radiosonde comparison. Sites MAW1, DAV1, CAS1, MCM4, BELG, SYOG and AMUN all show sub-millimeter GPS / AIRS biases. At the more humid Antarctic Peninsula sites, SMRT, PALM, OHI2, the GPS / AIRS comparison shows larger rms differences, biases and linear regression slopes greater than unity. At VESL, the large positive GPS / AIRS bias of 1.43 mm (40% GPS PW) suggests that the GPS measurements are perhaps systematically too large here. It is of note that SYOG shows a notably small GPS / AIRS mean bias of -0.14 mm, a closer agreement than the GPS / radiosonde agreement, albeit with larger scatter. This suggests the large GPS / radiosonde bias here originates at least partly in the radiosonde record. At AMUN there is close GPS / AIRS agreement, with a mean bias of -0.04 mm. The close agreement between GPS, radiosonde and AIRS at the very dry South Pole contradicts the suggestion by *Rama Varma Raja et al.* [2006] that the AIRS measurements are wet-biased in dry atmospheres. Finally, it is noted that the AIRS comparison is not conducted over the same period as the radiosonde comparison, due to there being no measurements in the austral winter. This is reflected in the larger mean PW values, and offers an explanation as to why the differences are larger than for the GPS / radiosonde comparison.

5.1.3 GPS / MODIS comparison

Scatter plots of the GPS / MODIS comparison and linear regression lines of best fit are found in Figure 10, with summary statistics in Table 4. The MODIS PW measurements show agreement to GPS that is comparable to that shown by AIRS, with an rms difference of 1.42 mm. The MODIS measurements tend to be 'wetter' than GPS and MODIS, however, with a mean GPS / MODIS bias of -0.35 mm. MODIS tends to therefore show better agreement, for this Antarctic study, with radiosonde measurements than with GPS. The level of the GPS / MODIS agreement is comparable to that seen for other, more humid regions of the globe in other comparative studies [e.g. *Li et al.*, 2003], who agree that MODIS NIR measurements are larger than GPS measurements of PW, with scale factors of 1.07 to 1.14. Our GPS / MODIS comparison shows similar levels of agreement to observations made by *Liu et al.* [2006], who note rms differences of 1.68 and 1.9 mm PW for locations on the Tibetan Plateau. Finally, the slope of the linear regression line at all sites is significantly less than unity, with a mean 0.78. As is the case with AIRS, the comparison is not conducted over the same period as GPS / radiosonde, explaining the larger mean PW values observed with MODIS.

6. Discussion

The high level of agreement now observed between GPS, radiosonde (sub-millimeter) and to a lesser degree to both AIRS and MODIS (typically, millimeter level), suggests that Antarctic PW from GPS could now be usefully assimilated into regional or global NWMs, as is already occurring elsewhere [e.g. *Yan et al.*, 2009], although for maximum use this would clearly require real time transfer of data and processing. Post-processed GPS data for Antarctica should therefore prove more useful for climate research, and assessment of NWM accuracy. The very dry atmosphere at AMUN means that this site represents an excellent test site for GPS PW accuracy in the future. It is not clear yet if all of the conclusions from this study (in particular the inter-technique comparison) apply equally to more humid sites in other regions.

Despite the promising results of the GPS analysis, there remain some limitations with regard to the usefulness of the GPS derived PW. We note that there are possibly site specific problems with the GPS observation data—or possibly the meteorological data and associated metadata—at a few GPS sites (e.g. SYOG and MCM4). At SYOG, GPS and AIRS agree, with a bias of 0.14 mm. The MODIS measurements, by contrast, show better agreement to radiosonde. Another potential cause of increased noise in GPS derived PW time series in Antarctica is snow accumulation on the antenna (e.g. DUM1).

PW measurements from the AIRS and MODIS instruments both offer encouraging levels of agreement with GPS, and are considered to offer potential over Antarctica for assimilation into NWMs. Additionally, perhaps more rigorous filtering of the data and further consideration of the size footprint employed over the topographically complex Antarctic coastal region, will result in a continued improved in agreement with the other techniques in the future.

7. Conclusions

We have presented an homogeneous and state-of-the-art GPS PW data set. Our reanalyzed GPS PW measurements are systematically drier than earlier GPS measurements (e.g. the IGS ZTD product). The up-to-date reanalysis of GPS data has brought Antarctic GPS PW measurements into a high level of agreement—with one notable exception—with radiosonde data, that has not been observed in previous comparative studies. Indeed, the reanalyzed GPS measurements are, if anything, marginally drier than the radiosonde measurements. We have not attempted to make corrections to the radiosonde data for the lag errors associated with the extreme cold temperatures, or any of the other radiosonde errors and biases. We, nevertheless suggest that a proportion, at least, of the often observed GPS / radiosonde bias, that has traditionally been explained wholly by the ‘radiosonde dry bias’, is explained by deficiencies in earlier GPS analyses. Most GPS derived datasets are considered to have been ‘wet biased’, until recently. There remain, no doubt, errors contributed by both GPS and radiosonde.

The fact that the reanalyzed GPS measurements generally show such a high level of agreement with the radiosonde derived dataset offers much confidence in the ability of GPS to make accurate PW measurement over the relatively dry Antarctic continent. Furthermore, the GPS agreement with other techniques, compared to the agreement observed in previous Antarctic studies that make use of the IGS product, such as *Vey et al.* [2004], is encouraging of its potential.

We have shown step-wise improvements in GPS PW when adopting absolute antenna phase centre variation models, the VMF1 MF, and *a priori* ZHD modeling. The introduction of each results in a significant jump in ZTD and PW. We note that the VMF1 MF and *a priori* ZHD are not included in the first, ongoing, IGS reprocessing effort, 'repro1'. Our results show therefore that any ZTD product derived from these IGS reprocessed orbits could readily be bettered using subsequent IGS reprocessing solutions. As of 2009, the IGS ZTD product should be used with caution—particularly if it is to be used as a means of validation of other instruments or techniques—until it is generated consistently with, at minimum, absolute PCVs, a *a priori* ZHD, and the VMF1 MF. For any GPS-derived ZTD product to be of use in climate related studies it is vital that it is derived from the 'best' possible set of homogeneously reanalyzed orbits. There remain further improvements that could be made in GPS reprocessing strategies; the most notable exceptions from our reprocessing are the second and higher order ionospheric corrections.

Finally, AIRS and MODIS level-2 satellite retrievals offer potential, complementing GPS by offering denser spatial sampling, although for optimum results further work is required on data filtering.

We note that with additional continuous GPS sites being deployed in remote locations, many co-located with meteorological sensors, that GPS PW coverage will hopefully in the future penetrate well into the interior of the Antarctic continent.

Acknowledgements

We would like to thank the following for making GPS data available for this project: International GNSS Service (IGS) community; British Antarctic Survey (BAS);

Alfred Wegener Institute, Bremerhaven. The research was funded by a NERC fellowship to Matt King and an EPSRC studentship to Ian Thomas.

We thank the anonymous reviewers for their constructive comments.

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Table 1. Summary of GPS locations and details of World Meteorological Organization (WMO) meteorological observing sites. The GPS WGS84 ellipsoidal heights and the geoid-ellipsoid separation (EIGEN-GL04c Geoid model) are used to compute the vertical offset, Δh, between the meteorological sensor and the GPS antenna.

	GPS Site ID	Longitude	Latitude	WMO ID	Met sensor height	GPS antenna ht. (WGS84)	Geoid-ellipsoid separation	Vertical offset, Δh
					(1)	(2)	(3)	(2) - (3) - (1)
					(mASL)	(m)	(m)	(m)
Syowa	SYOG	39.6	-69	89532	21.0	50.0	22.7	6.3
Mawson	MAW1	62.9	-67.6	89564	16.0	59.1	28.7	14.4
Davis	DAV1	78	-68.6	89571	23.0	44.4	18.1	3.3
Casey	CAS1	110.5	-66.3	89611	42.0	22.5	-16.9	-2.6
Dumont d'Urville	DUM1	140	-66.6	89642	43.0	-1.4	-41.1	-3.3
McMurdo	MCM4	166.7	-77.8	89664	24.0	98.0	-52.0	126.0
San Martin	SMRT	292.9	-68.1	89066	7.0	27.1	8.9	11.2
Palmer	PALM	296	-64.8	89061	8.0	31.0	16.8	6.2
O'Higgins	OHI2	302.1	-63.3	89059	10.0	32.5	23.0	-0.5
Belgrano	BELG	325.4	-77.9	89034	256.0	245.8	-11.2	1.0
Vesleskarvet	VESL	357.2	-71.7	89004	817.0	862.4	10.7	34.7
South Pole	AMUN	139.2	-90	89009	2830.0	2815.3	-27.1	12.4

Table 2. Summary of the current JPL IGS ZTD product estimation strategy, our 'base' processing strategy, and the fourth 'variant' strategy (final): 'Base+abs+VMF1+*a priori* ZHD+ATML'.

IGS ZTD product	'Base' (IGS ZTD product equivalent) strategy	'Base+abs+VMF1+*a priori* ZHD+ATML'
• GIPSY software: PPP strategy, using IGS orbits. • 7 degree elevation angle cut-off. • OTL. • Relative antenna PCVs (since pre-2006) • Niell MF (NMF) • Saastamoinen model and standard atmosphere for *a priori* ZHD.	• GAMIT software: global 60 station network, 30-hour arcs. • 7 degree elevation angle cut-off. • 1 tropospheric gradient estimated in N/S and E/W per day. • OTL (TPXO6.2 model) • Relative antenna PCVs. • Niell MF (NMF) • Saastamoinen model and standard atmosphere for *a priori* ZHD	• GAMIT software: global 60 station network, 30-hour arcs. • 7 degree elevation angle cut-off (10 degrees for Antarctic sites). • 1 tropospheric gradient estimated in N/S and E/W per day. • OTL model: (TPXO6.2 model). • Absolute PCVs (file igs1402.atx). • VMF1 MF. • *a priori* ZHD from observed surface meteorological data. • ATML: 'tidal '+ 'nontidal' model, as detailed by Tregoning and Watson [2009].

Table 3. Biases in ZTD (mm) for each model 'variant', relative to 'base' strategy for 2004: by individual site, averaged across the sites, and average biases introduced by each additional model. A negative bias indicates the 'variant' is drier than the 'base'.

Site ID	Bias in ZTD relative to 'Base' strategy (mm)				
	IGS	'Abs'	'Abs+VMF1'	'Abs+VMF1 +*a priori* ZHD'	Abs+VMF1+ *a priori* ZHD + ATML
SYOG	1.08	-8.59	-10.58	-11.84	-11.89
MAW1	0.24	-6.35	-9.11	-10.98	-10.92
DAV1	-0.25	-5.97	-8.73	-10.61	-10.60
CAS1	-1.91	-5.47	-7.93	-9.97	-9.95
DUM1	-	-8.86	-11.10	-13.50	-13.47
MCM4	-0.15	-6.57	-9.35	-10.99	-10.94
SMRT	-	-5.54	-7.93	-9.83	-9.84
PALM	-	-6.19	-7.99	-9.57	-9.58
OHI2	0.74	-6.16	-7.94	-9.34	-9.35
BELG	-	-4.81	-7.66	-9.24	-9.29
VESL	-3.17	-8.15	-10.60	-12.49	-12.54
AMUN	-	-2.32	-7.31	-10.79	-10.78
Mean ZTD bias to 'base' strategy (mm)	-0.49	-6.25	-8.85	-10.76	-10.76
Mean ZTD bias introduced by each 'new' GPS model (mm)	-	-6.25	-2.60	-1.91	0.00

		East Antarctica						West Antarctica					S. Pole	
		SYOG	MAW1	DAV1	CAS1	DUM1	MCM4	SMRT	PALM	OHI2	BELG	VESL	AMUN	Mean
GPS / Radiosonde	Mean GPS PW (mm)	2.50	2.47	4.09	4.99	4.06	2.67	-	-	-	-	-	0.58	
	Mean Radiosonde PW (mm)	4.78	3.05	3.79	4.74	4.77	2.83	-	-	-	-	-	0.49	
	Bias (mm)	-2.28	-0.58	0.29	0.25	-0.71	-0.15	-	-	-	-	-	0.08	-0.44
	rms difference (mm)	2.50	0.99	0.84	0.64	1.60	0.79	-	-	-	-	-	0.42	1.11
	Standard deviation difference (mm)	1.02	0.80	0.79	0.59	1.43	0.78	-	-	-	-	-	0.41	0.83
	Slope	0.88	1.01	1.05	1.08	1.02	0.97	-	-	-	-	-	0.57	0.94
	Intercept (mm)	-1.72	-0.62	0.11	-0.14	-0.79	-0.07	-	-	-	-	-	0.36	-0.41
	Correlation	0.87	0.94	0.94	0.98	0.86	0.90	-	-	-	-	-	0.50	0.86
		SYOG	MAW1	DAV1	CAS1	DUM1	MCM4	SMRT	PALM	OHI2	BELG	VESL	AMUN	Mean
GPS / AIRS	Mean GPS PW (mm)	3.45	2.54	4.51	4.57	4.19	3.22	6.15	6.96	6.22	2.79	3.98	0.69	-
	Mean AIRS PW (mm)	3.32	2.71	3.78	3.57	2.58	3.21	3.80	4.83	4.79	2.70	2.54	0.73	-
	Bias (mm)	0.14	-0.16	0.73	1.00	1.61	0.01	2.35	2.13	1.43	0.09	1.43	-0.04	0.89
	rms difference (mm)	1.27	1.07	1.47	1.67	2.59	0.82	3.13	2.84	2.04	0.82	1.60	0.35	1.64
	Standard deviation difference (mm)	1.26	1.05	1.27	1.33	2.03	0.82	2.08	1.88	1.46	0.82	0.72	0.35	1.26
	Slope	0.87	0.99	0.95	1.08	1.05	0.83	1.11	1.25	1.25	1.03	0.95	0.43	0.98
	Intercept (mm)	0.63	-0.12	1.39	1.03	1.48	0.55	1.94	0.94	0.22	0.00	1.54	0.38	0.83
	Correlation	0.70	0.83	0.79	0.87	0.63	0.79	0.56	0.81	0.90	0.77	0.88	0.37	0.74
		SYOG	MAW1	DAV1	CAS1	DUM1	MCM4	SMRT	PALM	OHI2	BELG	VESL	AMUN	Mean
GPS / MODIS	Mean GPS PW (mm)	3.18	2.78	4.39	4.85	3.55	3.37	5.69	6.38	6.93	2.88	3.50	-	
	Mean MODIS PW (mm)	4.65	3.48	5.02	4.70	4.24	3.45	6.11	6.43	7.01	2.99	3.25	-	
	Bias (mm)	-1.46	-0.69	-0.63	0.15	-0.69	-0.09	-0.42	-0.04	-0.08	-0.11	0.25	-	-0.35
	rms difference (mm)	2.07	1.32	1.29	1.18	1.78	0.82	1.54	1.68	1.90	0.89	1.13	-	1.42
	Standard deviation difference (mm)	1.46	1.13	1.12	1.17	1.64	0.82	1.48	1.68	1.90	0.88	1.10	-	1.31
	Slope	0.56	0.85	0.70	0.82	0.92	0.83	0.63	0.82	0.87	0.78	0.65	-	0.77
	Intercept (mm)	0.49	-0.16	0.87	1.02	-0.35	0.51	1.84	1.10	0.86	0.55	1.39	-	0.74
	Correlation	0.69	0.86	0.87	0.90	0.81	0.85	0.76	0.83	0.84	0.73	0.81	-	0.81

Table 4. GPS versus radiosonde, AIRS and MODIS comparison summary statistics. As in the text, the difference 'GPS / AIRS' means the difference (GPS-AIRS).

Figure 1. Typical daily network of GPS sites, that used on 1 July 2004.

Figure 2. Location map showing locations of 12 Antarctic GPS sites used in the study (triangles) and sites where radiosonde data are available (solid triangles).

Figure 3. ZTD differences between 'base' and each model 'variant' solution, by site. Plotted is 'variant' minus 'base', i.e. negative values indicate that the 'variant' is drier than the 'base'. Variants are (i) IGS product (blue line); (ii) 'base+abs PCVs' (red line); (iii) 'base+abs PCVs+VMF1' (cyan line); (iv) 'base+abs+VMF1+a priori ZHD' (magenta line); (v) 'base+abs+VMF1+a priori ZHD' (black line); (v) radiosonde (green line). Differences have been smoothed using a 7-day moving average. (Note the black line representing model variant (v) cannot be distinguished from the magenta line representing model variant (iv)).

Figure 4. Absolute PW: GPS (blue dots), AIRS (black dots), MODIS (pink dots) and radiosonde (green dots) for 2004, for East Antarctic sites in order of increasing longitude, from SYOG to MCM4

Figure 5. As Figure 4, for remaining sites, ordered by increasing longitude from SMRT to VESL, and AMUN (note the different scale for AMUN).

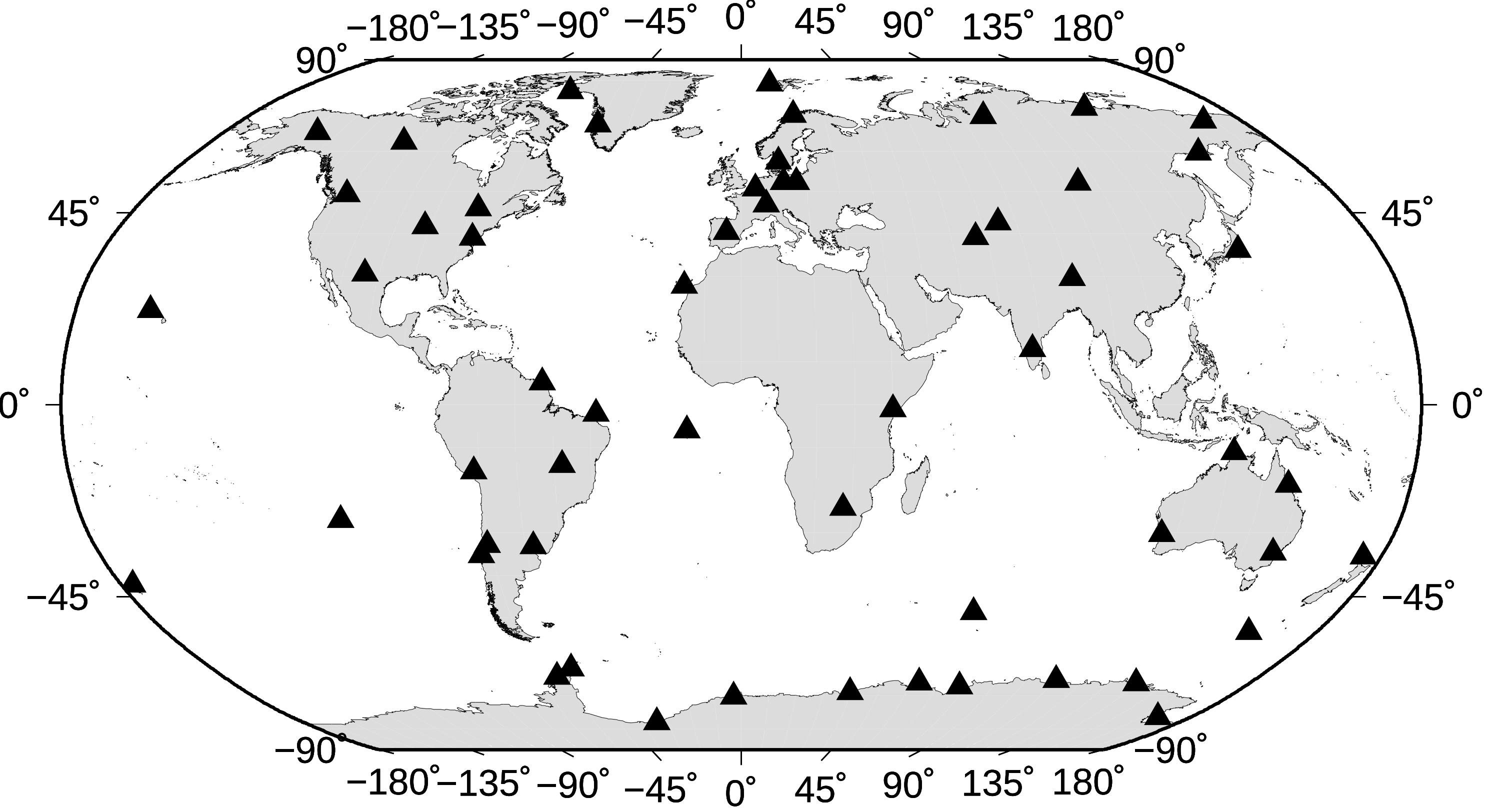
Figure 6. PW difference from GPS PW for sites SYOG to MCM4: AIRS (black dots), MODIS (pink dots) and radiosonde (green dots). Positive values indicate the measurement to be 'wetter' than GPS.

Figure 7. As Figure 6 for remaining sites, SMRT to VESL and AMUN.

Figure 8. Scatter-plots of GPS versus radiosonde measurements of PW. 2-hourly GPS values have been linearly interpolated to the radiosonde observation epoch. 1 sigma error bars are indicated, along with slope and correlation, R. Note the different scale for AMUN

Figure 9. As Figure 8, for the GPS / AIRS comparison. Note the different scale for AMUN.

Figure 10. As Figure 8, for the GPS / MODIS comparison. Note the different scale for AMUN.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45°
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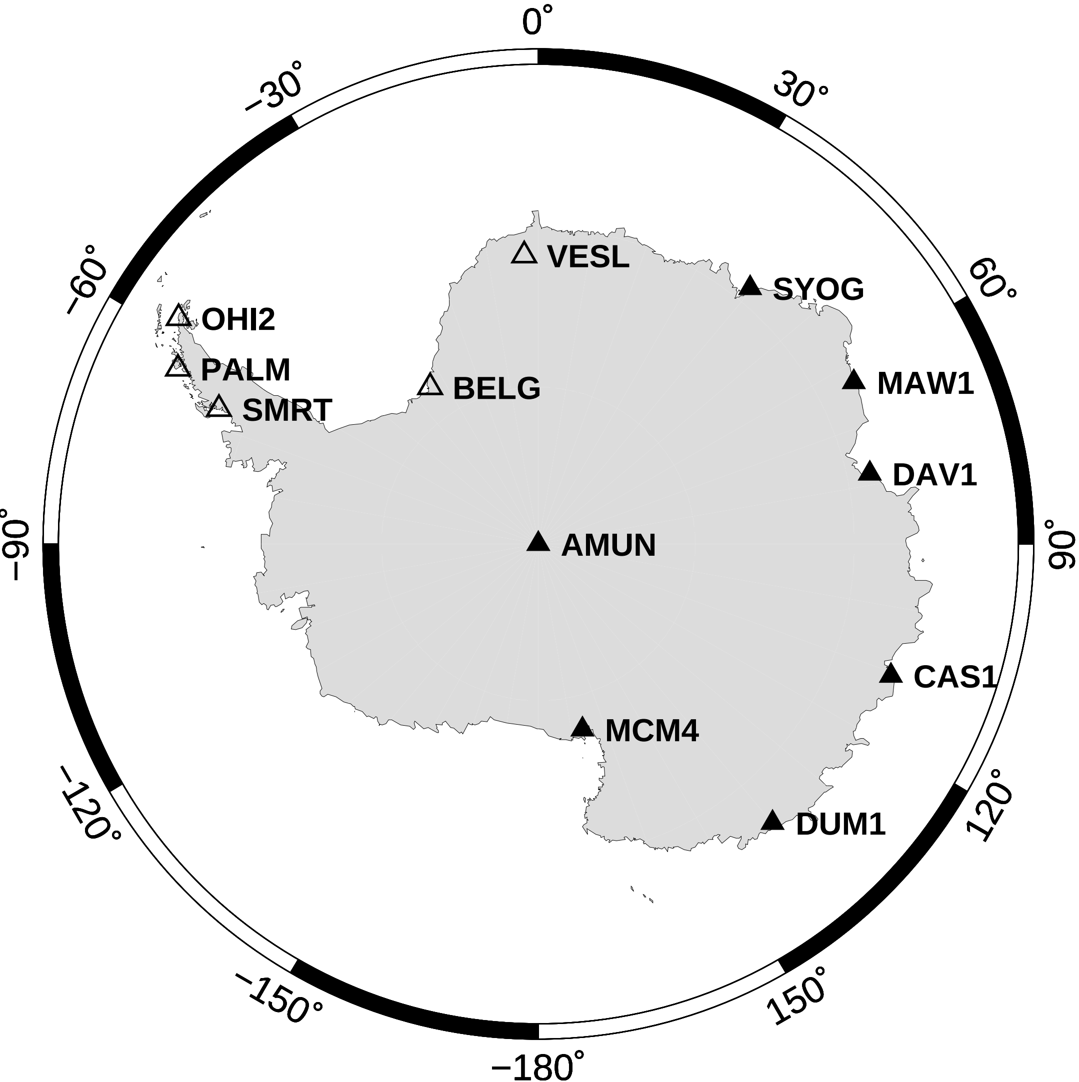
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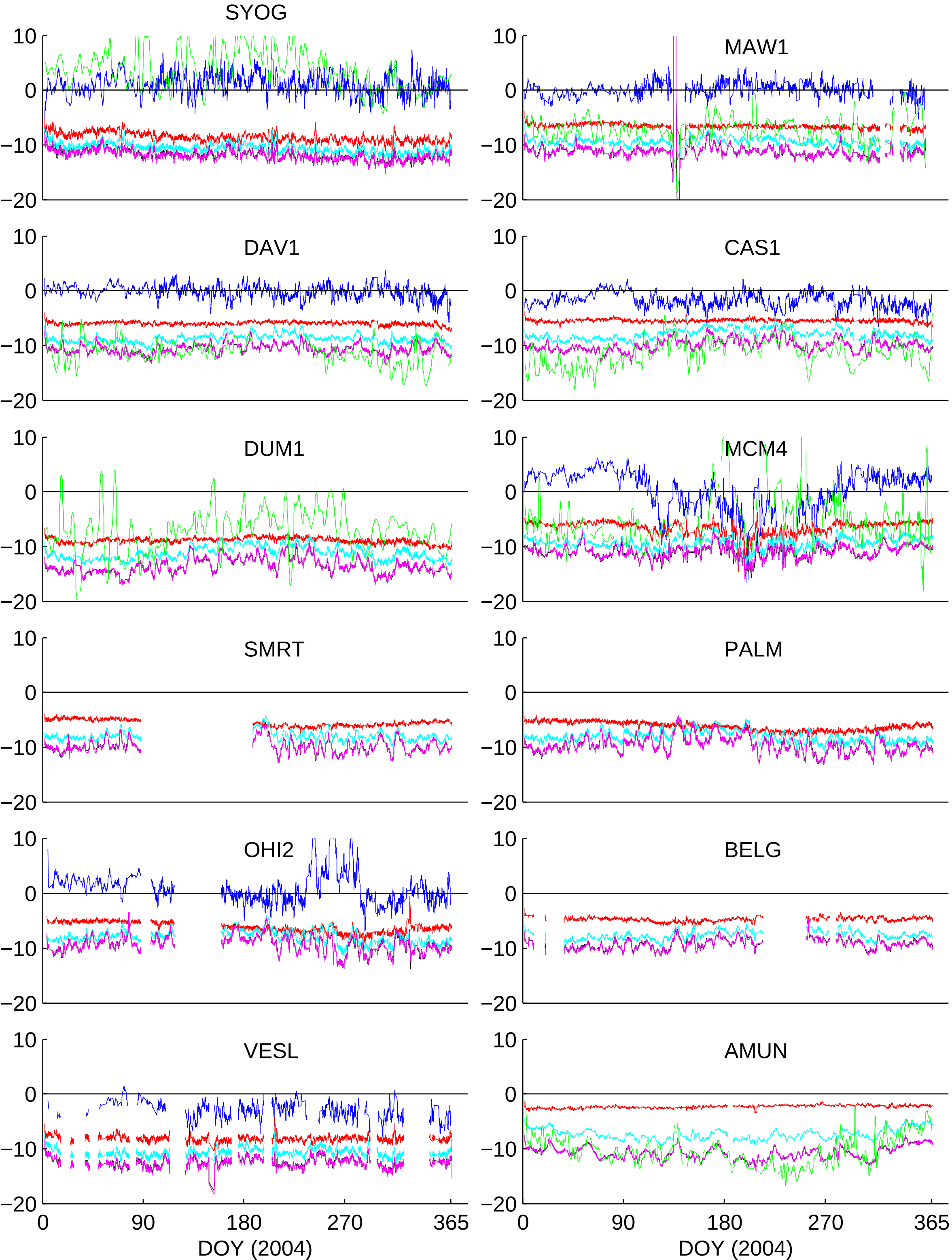
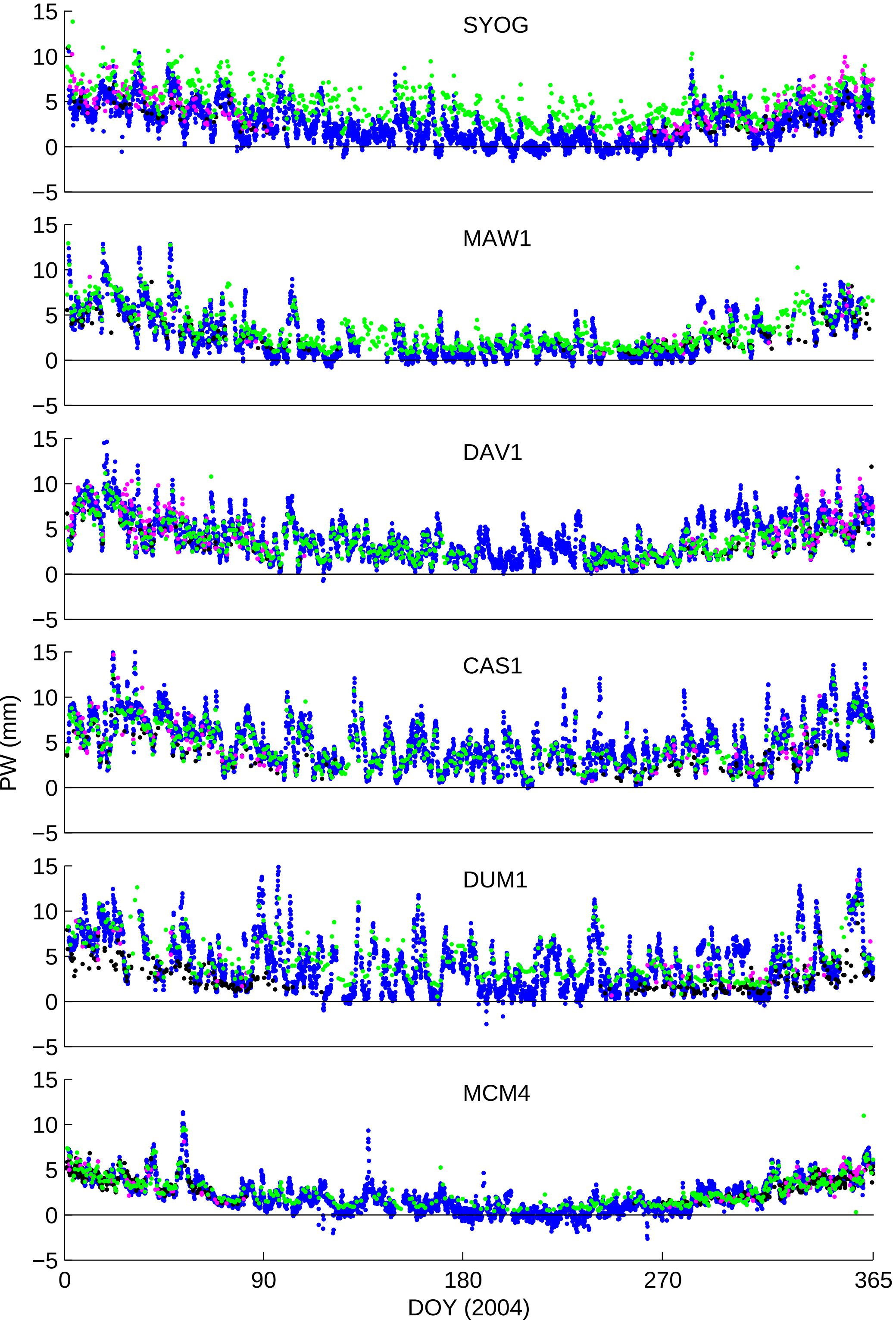
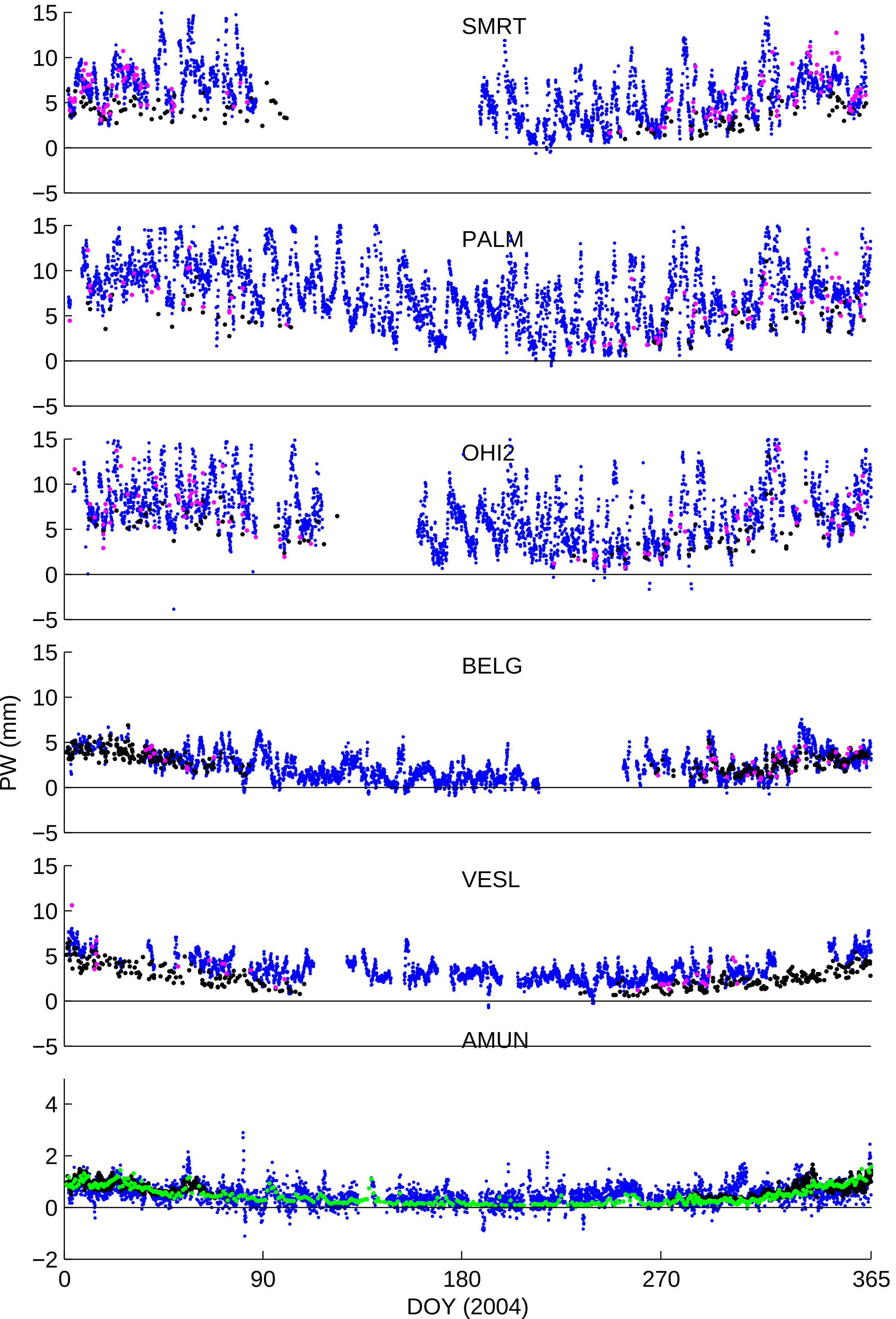
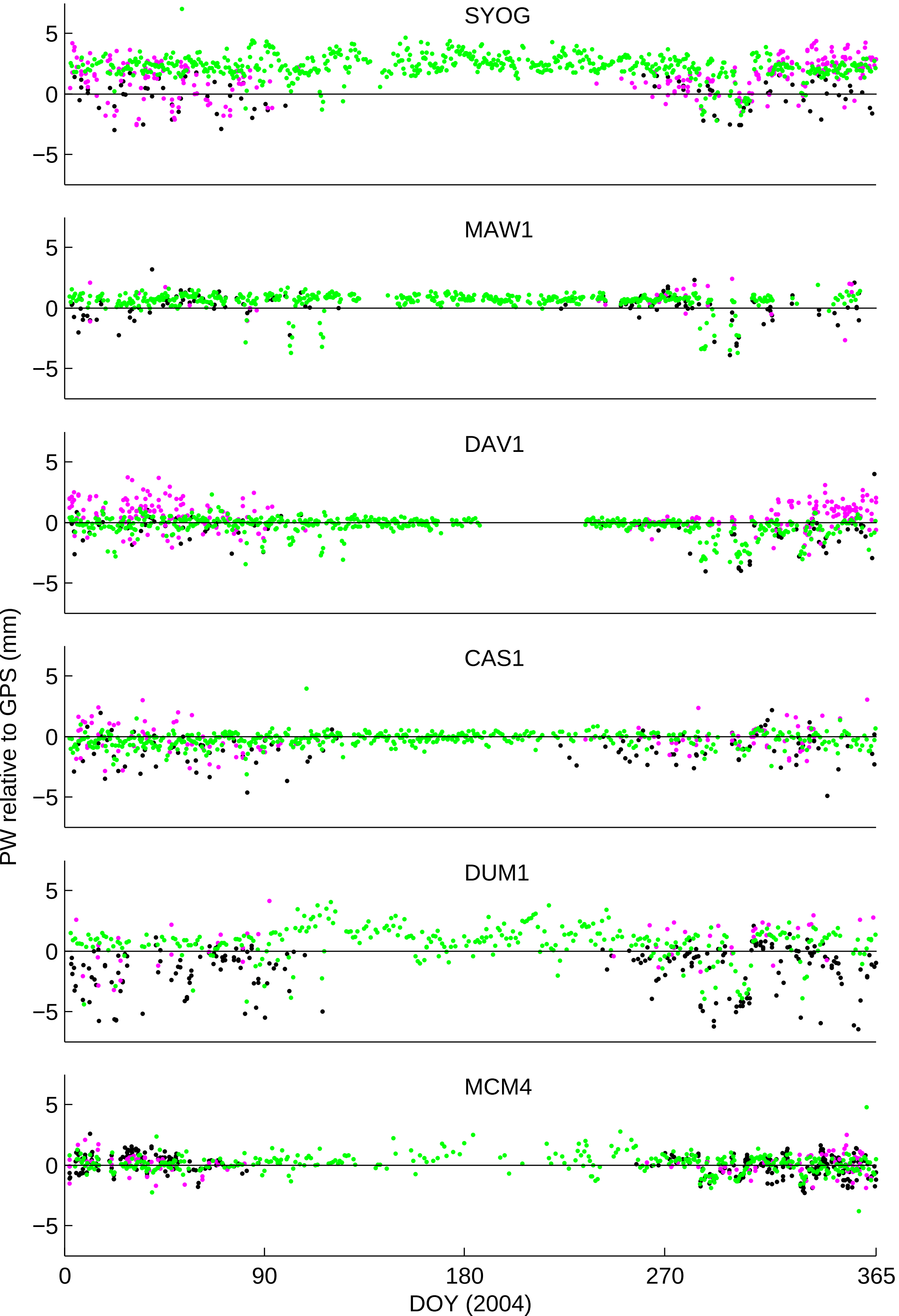
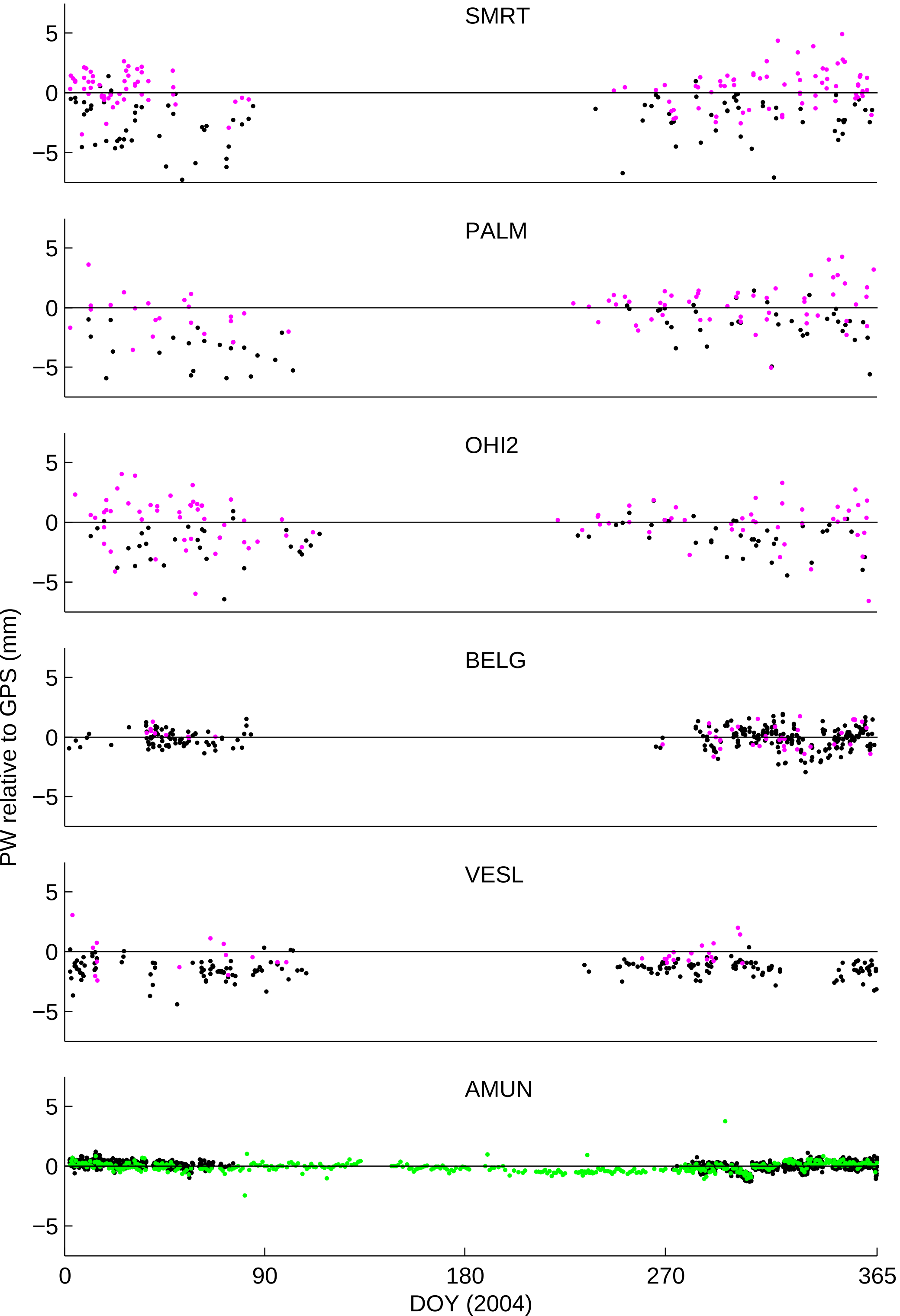
30°
60°
90°
120°
150°
−180°
−150°
−120°
−90°
−60°
−30°
VESL
SYOG
OHI2
PALM
SMRT
BELG
MAW1
DAV1
AMUN
CAS1
MCM4
DUM1

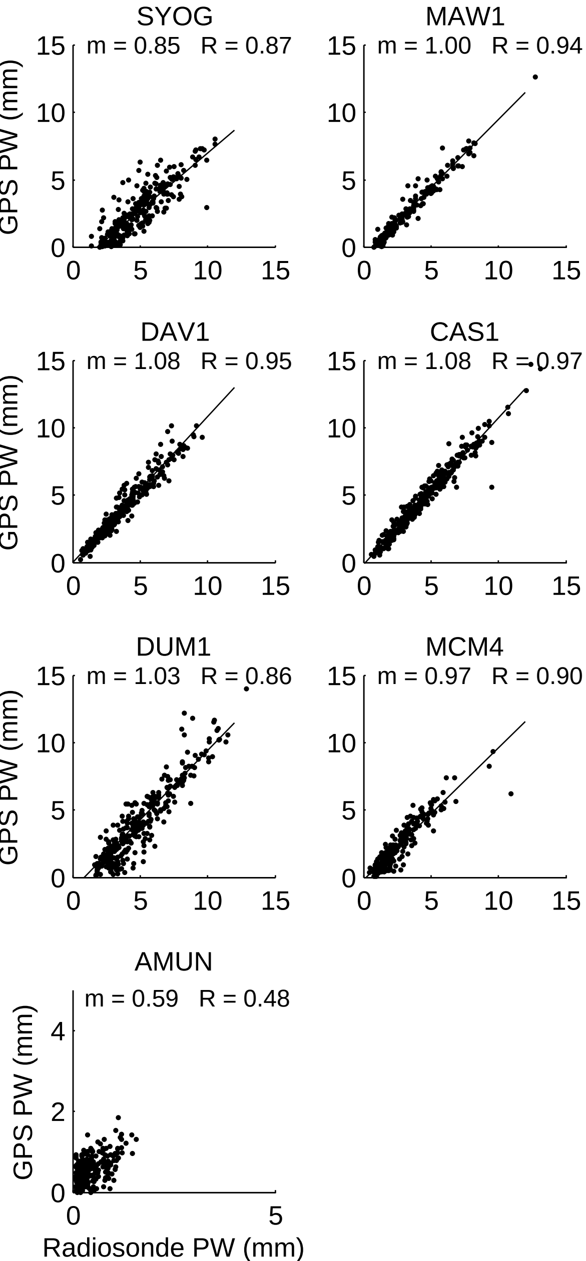

SYOG
MAW1
DAV1
CAS1
DUM1
MCM4
SMRT
PALM
OHI2
BELG
VESL
AMUN
10
0
−10
−20
0
90
180
270
365
DOY (2004)
DOY (2004)


SYOG
MAW1
DAV1
CAS1
DUM1
MCM4
PW (mm)
DOY (2004)
15
10
5
0
−5
0
90
180
270
365


SMRT
PALM
OHI2
BELG
VESL
AMUN
PW (mm)
DOY (2004)
15
10
5
0
−5
4
2
0
−2
0
90
180
270
365


SYOG
MAW1
DAV1
CAS1
DUM1
MCM4
5
0
−5
PW relative to GPS (mm)
0
90
180
270
365
DOY (2004)


SMRT
PALM
OHI2
BELG
VESL
AMUN
5
0
−5
PW relative to GPS (mm)
0
90
180
270
365
DOY (2004)


SYOG
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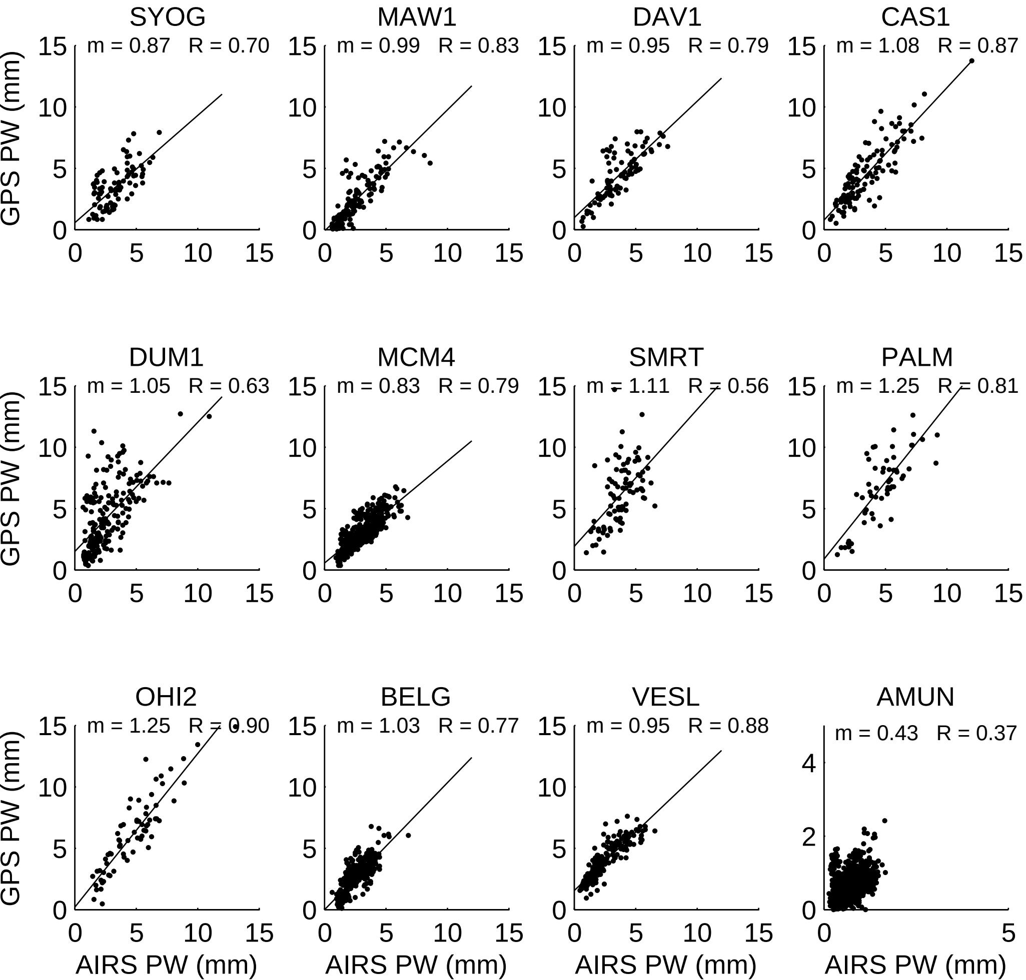
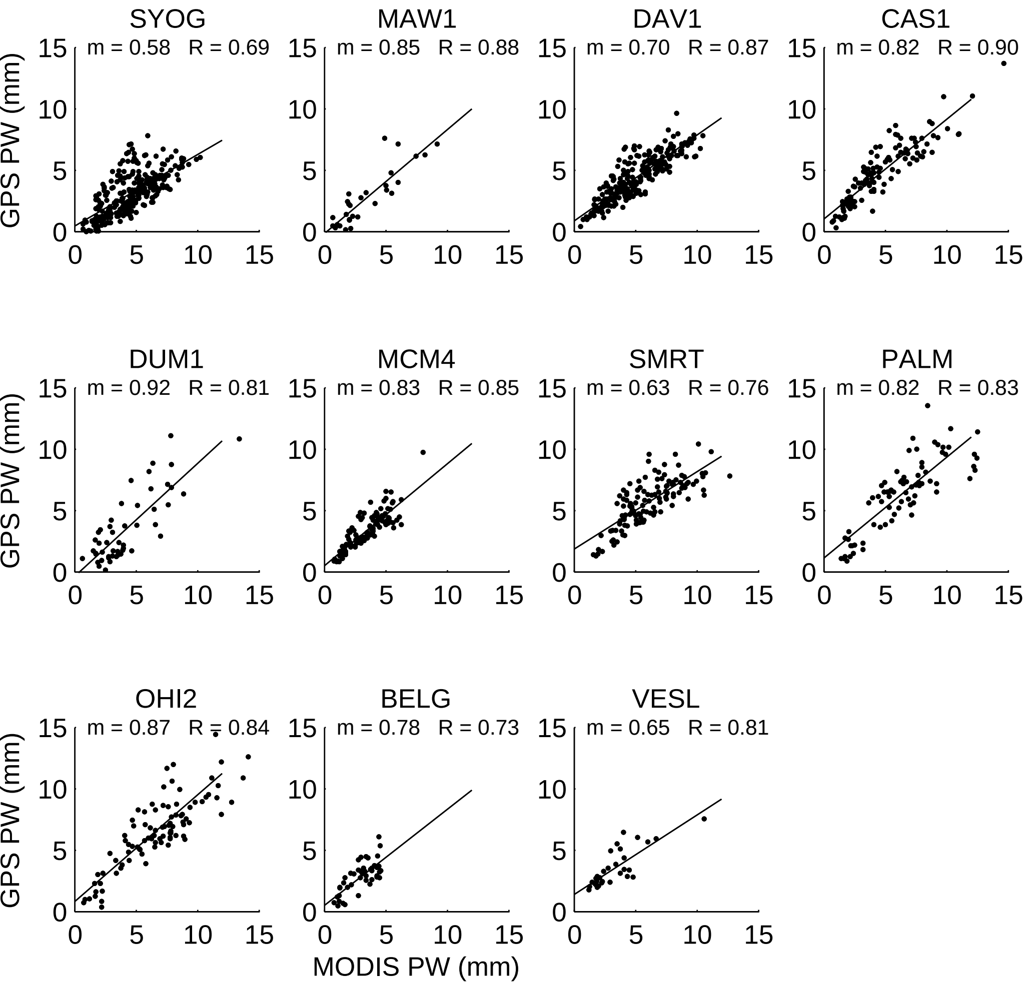
MAW1
m = 1.00 R = 0.94
DAV1
m = 1.08 R = 0.95
CAS1
m = 1.08 R = 0.97
DUM1
m = 1.03 R = 0.86
MCM4
m = 0.97 R = 0.90
AMUN
m = 0.59 R = 0.48
GPS PW (mm)
Radiosonde PW (mm)
0
5
10
15
0
2
4
5


SYOG
m = 0.87 R = 0.70
MAW1
m = 0.99 R = 0.83
DAV1
m = 0.95 R = 0.79
CAS1
m = 1.08 R = 0.87
DUM1
m = 1.05 R = 0.63
MCM4
m = 0.83 R = 0.79
SMRT
m = 1.11 R = 0.56
PALM
m = 1.25 R = 0.81
OHI2
m = 1.25 R = 0.90
BELG
m = 1.03 R = 0.77
VESL
m = 0.95 R = 0.88
AMUN
m = 0.43 R = 0.37
GPS PW (mm)
AIRS PW (mm)
0
5
10
15
2
4


SYOG
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MAW1
m = 0.85 R = 0.88
DAV1
m = 0.70 R = 0.87
CAS1
m = 0.82 R = 0.90
DUM1
m = 0.92 R = 0.81
MCM4
m = 0.83 R = 0.85
SMRT
m = 0.63 R = 0.76
PALM
m = 0.82 R = 0.83
OHI2
m = 0.87 R = 0.84
BELG
m = 0.78 R = 0.73
VESL
m = 0.65 R = 0.81
GPS PW (mm)
MODIS PW (mm)
0
5
10
15