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Comparison between GNSS ground-based and GPS radio occultation precipitable water observations over ocean-dominated regions

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Abstract

Precipitable water (PW) inferred from GPS (Global Positioning System) radio occultation (RO) and ground-based (GB) Global Navigation Satellite System (GNSS) observations are compared between years 2007 and 2014. As previous studies were mainly performed over continental areas we now focus over ocean-dominated geographical areas. Our analysis is done in order to find out how the reliability level of RO results over oceanic areas compares to land. As RO soundings usually miss some information close to the ground, we also assess different methods to complete the lacking data. We found 47 terrestrial stations that lie in islands small and far away from continental areas where the weather might be governed by the sea conditions. From comparisons of almost 5000 collocated samples, PW from RO and GB exhibit a global mean difference around 1 mm, root-mean-square deviation about 5 mm and a correlation above 0.9. The 2007-2014 timeseries and the monthly mean RO and GB PW were also

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compared to reanalyses per hemisphere, latitude regions and oceans. In each zone it was found that PW from RO, GB and reanalyses all exhibit in general consistent seasonal qualitative behavior. However, quantitative differences exist between reanalyses on one side and RO and GB on the other side. We also conclude that RO and GB seem to be more sensitive for the detection of features that depart from the regular annual cycle.
Keywords: precipitable water, GPS radio occultations, GNSS ground-based retrievals

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1. Introduction

Precipitable water (PW) contemplates the amount of water that can be obtained from the surface to the top of the atmosphere including the liquid and (condensed) vapor phases. It significantly influences many atmospheric processes. In addition, this information can be an important input for hydrological and radiation models in the atmosphere. Observations from satellite passive infrared or microwave sensors have been used to study PW behavior over space and time, but these methods have some shortcomings. Microwave measurements exhibit difficulties over land, whereas infrared observations cannot provide accurate information below the clouds. In contrast, the Global Positioning System (GPS) radio occultation (RO) technique is applied to obtain PW over land and ocean under all-weather conditions (Kursinski et al., 1997). GPS RO is a unique satellite technique regarding the retrieval of global and continuous atmospheric information. During our study period it provided about 2000 global daily profiles of water vapor, temperature, refractivity and pressure from the troposphere up to the middle stratosphere. However, it also has pitfalls. One of the most challenging aspects is related to the fact that these retrievals do not usually reach the ground. Therefore the water vapor profiles need somehow to be completed in the lowest part and the corresponding uncertainty in the calculated PW has to be evaluated according to each of the different available methods (e.g., Teng et al., 2013). Some works performed comparisons between the PW inferred from the different satellite techniques for observations nearly collocated in space and time (e.g., Wick et al., 2008; Ho et al., 2010; Teng et al., 2013).

The ground-based (GB) Global Navigation Satellite System (GNSS) also represents a very promising tool for the observation of PW (Duan et al., 1996; Tregoning et al., 1998; Calori et al., 2016) with an accuracy level similar to that expected from the satellite measurements (Wang et al., 2007; Vey et al., 2010). However, the corresponding terrestrial stations are only located over land and are not evenly distributed. Recent works have analyzed the complementarity potential of GPS RO and GB GNSS due to their global and permanent measurements but different specific characteristics and some of these studies have compared their outcomes (e.g., Bonafoni and Biondi, 2016; Kuleshov et al., 2016).

Until now humidity above the ocean has been compared among data obtained by diverse satellite techniques (e.g., Mears et al., 2012; Teng et al., 2013), so here we follow a different approach. This work aims to verify GPS RO PW over ocean by comparing it with the values inferred from GB GNSS above small islands away from the continents, where the conditions might be mainly dictated by the surrounding ocean. We depart from the procedure by Huang et al. (2013), who considered the GB GNSS PW measurements as the "truth". Here we establish comparisons between data from both observational methods and further test them against reanalyses from the National Center for Environmental Prediction (NCEP) and European Centre for Mid-range Weather Forecasting (ECMWF).

In Section 2 we describe our data and explain our processing methods. In Section 3 we exhibit our results comparing PW obtained by GPS RO and by GB GNSS. The possible relation of PW discrepancies between both in collocations is analyzed against distance or time separation between them, the handling of missing RO values at the lowest levels and the height of the GB station. Then we also study the monthly means and time evolution of RO, GB and reanalyses from NCEP and ECMWF for diverse geographical areas. In Section 4 we present the conclusions.

2. Data and method

We used the GB PW data product derived from averages over a 2 h interval at the National Center for Atmospheric Research (NCAR) between years 2007 and 2014. No data previous to year 2007 were considered in our study because the amount of RO profiles increased significantly in the last part of year 2006. By using a unique data provider we ensure that the study will have no biases due to the use of different processing procedures to obtain GB PW. The PW calculations are based on GB GNSS zenith path delay observations obtained at IGS (International GNSS Service) stations. There were no PW products derived from IGS data available for download for the year 2015 and later at NCAR. A detailed explanation of the NCAR procedure may be found in Wang et al. (2007), mainly in their Figure 3. In summary, when traveling from the GPS satellites to the GB receivers, the radio signals are slowed in the lower neutral atmosphere (tropospheric delay). This effect can be divided into two parts the hydrostatic delay, which is mainly a function of the surface pressure at the GPS receiver, and the wet delay, which depends strongly on the total amount of water vapor along the signal trajectory and weakly on the atmospheric temperature. GPS receivers detect information from several satellites at the same time. These signals arrive from different angles and lead to the calculation of the total delay along the zenith direction by means of a mapping function. The hydrostatic part can be estimated from the surface pressure with good accuracy. The wet component can be inferred from the difference between the total and the hydrostatic delays, which leads to PW if surface pressure and temperature are provided at the station.

The present study used the so-called wet profiles of the re-processed data (highest quality) products from all available RO missions between years 2007 and 2014 (COSMIC, CHAMP, METOPA, METOPB) provided by CDAAC (COSMIC Data Analysis and Archive Center). These humidity profiles have already been successfully tested against other datasets from satellites, radiosonde and reanalyses (e.g., Wang et al., 2013; Vergados et al., 2015, 2018). To calculate PW, we first derived specific humidity q from water vapor pressure (e) provided by GPS RO as usual by

$$q = 0.622 \frac{e}{p_d + e} \tag{1}$$

where p_d is the partial pressure of the dry air. Then

$$\mathrm{PW} = -\frac{1}{g} \int_{p_s}^{p_t} q \, dp \tag{2}$$

where g is gravity and p_s and p_t refer respectively to the pressure p at the surface and the top of the considered atmospheric column. Usually the GPS RO measurements do not reach the ground. Following Teng et al. (2013); Huang et al. (2013) we filled the missing lowest levels of water vapor with a least-square fitting, but we also tested two other completing alternatives provided by CDAAC for most but not all profiles: ECMWF and NCEP analysis model (respectively TOGA and GFS) values. To obtain PW we integrated specific humidity from the IGS station surface to 10 km height. Our final data products were PWROls (least squares), PWROecm and PWROgfs. The outcomes of the three filling methods were compared against GB results and reanalyses. In both observational techniques the PW may be regarded as a kind of horizontal average over about 200 km.

To ensure that oceanic conditions dominate the local weather we considered the GB GNSS stations only if they were located in islands that were at least 500 km away from any continent and if their size was less than 40,000 km^2, whereby 47 have been found matching these conditions (see Figure 1). Following similar criteria by Huang et al. (2013) we defined a GB GNSS and GPS RO close encounter as a collocation if the distance between both was less than 200 km and the time separation less than 2 h. In addition, it was requested that the lowest RO point should not be more than 1000 m above the GB station in order to reduce calculation errors. From the 47 stations, 2 of them had no collocations with RO and 4 had a to short data record. In Table 1 we present some basic information of each station. We first compared PW for collocations between GPS RO and GB GNSS. There are typically a few collocated RO retrievals per month for every GB station. As some stations are close to each other, they may be using the same GPS RO retrieval in some cases. For time evolution and monthly mean regional comparisons we used reanalysis PW every 6 h from ECMWF and from NCEP (respectively 0.75^ox0.75^o and 2.5^ox2.5^o horizontal resolutions) interpolated to each GB station location and time of profile.

3. Results

We first compare PW from the GB GNSS with the collocated GPS RO between years 2007 and 2014. Figure 2 shows a scatterplot of the values from both sources and the line that best fits all the points. We evaluated for GPS RO the three different methods mentioned above for completion of the lowest missing levels of water vapor. We show in each case the root-mean-square (RMS) difference, correlation value, mean difference, the slope and intercept and their standard error and the number of collocated pairs. The three cases exhibit a clear linear relationship with a slope close to 1. For comparison, Huang et al. (2013) obtained mainly over land with the least squares filling method a slope of 1.004, a correlation of 0.96, RMS = 3.25 mm and a mean difference of 0.32 mm. Our values are in general slightly worse. However, this may be a consequence that we included height differences of 1000 m between the lowest RO point and the station altitude instead of 500 m (to keep more collocated pairs). For their remaining calculations Huang et al. (2013) also used a 1000 m difference. For PWROls there are some significant outliers, where RO overestimates GB by more than 10 mm, which represent about 15 % of the total dataset. This occurs mainly at the lowest PW values. No specific months or regions were found for this behavior. As explained above not all RO have been filled at CDAAC with reanalysis data, so there are less cases for PWROecm and PWROgfs. Both quantities do not show a significant amount of outliers at the lowest values and therefore exhibit a better statistical performance than PWROls.

In general, as both soundings of all the collocated pairs are not exactly in the same place and time, spatiotemporal variability may lead to some of the discrepancies (along with the inherent errors of the two experimental techniques). Now we assess this effect and evaluate if the absolute value of the differences dPW tends to disappear when the horizontal distance dx of the collocations tends to zero, or equivalently if one method has a persistent bias with respect to the other one. We also evaluate the effects of the vertical distance between the lowest point of the RO and the station dz and the effect of the GB station height dh. In Figure 3 we show these relationships in three panels. The rising dPW trend for increasing dx, dz and dh are clear. Deviations do not tend to zero for decreasing parameters, so there are intrinsic biases between the GPS RO and GB GNSS methods. However, dPW apparently does not exhibit a linear behavior at low dz and dh values and a sharper approach towards 0 seems to be plausible. Regarding the increasing discrepancies against GB station height, these may emerge because the particular conditions at an island topography may not be representative of the characteristics sounded by the GPS RO in a probable flat region up to 200 km away. Also, in Figure 3 dPW is represented against dh up to 1500 m because the two stations above 3000 m show small discrepancies as PW tends to be much lower at those heights (increases might be seen only if relative instead of absolute PW differences are shown). Although the nearly linear behavior in the three panels is clear, there is some significant scattering. This characteristic may be attributed to the diversity of regions and seasons that contribute to each of the represented relations. No significant behavior could be detected against time difference between both measurements in each collocation.

We further assess whether the station height has any influence on the discrepancies between PW from ROls, GB and reanalyses. This seems a priori quite plausible as water content above small high areas may be quite different from plain surrounding zones at sea level. We show in Figure 4 the PW time evolution for ROls, GB and reanalyses for three stations that are below 30 m above sea level in the Northern Hemisphere (NH), two of them at high latitudes and one at middle latitudes, and three stations above 500 m, two of them at mid-latitudes in the NH and one in the low latitude region in the Southern

Hemisphere (SH), for more station details see Figure 1 and Table 1. The three former stations exhibit consistent behavior for the four PW sources, whereas the latter ones clearly exhibit the disturbing effect of station altitude on PW estimation by different methods (in some cases there are more than 100 % differences). Moreover, PW from reanalyses exhibits a remarkable irregular behavior in the three lower panels of Figure 4.

In Figure 5 we show the monthly means of PW over the 8 years in the SH and NH according to ROls, ROecm, ROgfs, GB and both reanalyses (not over the whole grid and month but only evaluated at the positions and times of the collocation pairs). There were 21 GB stations in the NH and 10 in the SH. Seasonal behaviors are all similar but there are quantitative discrepancies. Differences between ROls and GB are in general less significant than discrepancies with respect to reanalyses. RO filled with analyses show a kind of intermediate behavior.

We now perform an analysis based on 5 latitude bands: low (between 30^o and -30^o), middle (between 30^o and 60^o in both hemispheres) and high latitudes (between 60^o and 90^o in both hemispheres). The latitude bands from North to South respectively have 3, 3, 31 and 4 stations, whereas the high latitude band in the SH was excluded because it does not have a minimum acceptable space and time coverage for statistical purposes (see Table 1). In each of the 4 latitude bands shown in Figure 6, PW curves from GPS RO, GB GNSS and reanalyses show consistent monthly evolution and similar timeseries behavior over the 8 years studied. The RO values are shown for the 3 methods filling the lowest missing levels. From the timeseries plots it becomes clear that RO and GB seem to be more sensitive to specific departures from cyclic annual behavior whereas the reanalyses in general regularly repeat the yearly patterns. Again, in general ROls and GB stay close together in a range of values and both reanalyses on another range, whereas ROecm and ROgfs show some intermediate behavior.

Finally we compare PW data according to the ocean (and hemisphere). Only the Pacific Ocean exhibited sufficient data for good statistical power on both hemispheres (8 stations in the SH and 10 stations in the NH), whereas we performed calculations for the Atlantic Ocean in the NH (17 stations) and Indic Ocean in the SH (5 stations). In Figure 7 we show the monthly evolution and the whole timeseries. We may see again in the timeseries the apparent clearer detection of specific departures from the regular yearly behavior by RO and GB with respect to reanalyses but they all exhibit similar qualitative characteristics. Notice again that in general, ROls and GB show a similar range of values and both reanalyses another range, whereas ROecm and ROgfs stay roughly in between.

Although qualitative behaviors are similar, notice that mainly in panels a and c in Figure 7 there are significant PW differences for reanalyses against GB and RO. Discrepancies are essentially in the 10-20 mm range. This problem may be attributed to the deficient representation of the terrain height by both models in some regions, which is a key parameter in the adequate calculation of PW (see Equation (2)), as the largest values of specific humidity are typically found in the lowest atmospheric layers. After removal of the places where the station heights and the models differ by more than 200 m, both panels lead to Figure 8, where reanalyses, GB and RO show qualitative and quantitative agreement. In Table 2 we show the removed stations and the height differences. In reference to panels a and c in Figure 7 notice that over and underestimation of terrain height in the models leads respectively to the inverse effect in PW.

4. Conclusions

- Different filling methods of water vapor in the lowest levels of GPS RO may lead to some individual significant differences in PW estimation.
- PW from RO and GB exhibit a global mean difference around 1 mm and a correlation above 0.9. Global root-mean-square differences stay about 5 mm, which on average represents a discrepancy in the 15-20 %. Deviations up to 40 % have been found in some geographical areas between reanalysis and GB observations at seasonal scales (Vey et al., 2010).

- We assessed differences that emerge in the measurement of PW by RO and GB due to horizontal and vertical separation of the sounding sites, time difference and height of the station. No significant difference was only found for time difference within 2 hours. By letting the other parameters approach 0 it becomes revealed that an intrinsic bias between GB and RO exists.

- PW results at high islands exhibit remarkable differences between ROls and GB values on one side and reanalyses on the other side. This discrepancy may be attributed to the incapacity of reanalyses to describe these very particular local conditions.

- RO, GB and reanalyses PW estimations show similar qualitative but in general different quantitative behavior. The largest absolute differences may in general (but not always) be found in the seasons and regions with the largest PW values. The typical pattern is that both reanalyses are similar to each other and GB and ROls resemble each other, whereas ROecm and ROgfs exhibit an intermediate behavior.

- PW obtained by reanalyses is trustworthy only in regions where the terrain height in these models is represented adequately. Otherwise GB and RO are more reliable.

- In timeseries GB and RO seem to be more sensitive for the detection of departures from the regular annual cycle than reanalyses.

- The future increase of GB GNSS observations and GPS RO retrievals may add statistical strength to some of the results here highlighted or may allow to reveal some weaker effects that we were not able to detect.

- The present results and those by Huang et al. (2013); Teng et al. (2013) indicate that GPS RO data may be an extraordinary observational tool for the spatial and temporal monitoring of the behavior of water vapor over the whole planet.

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Table 1: GB GNSS station information

#	Name	Height* (m)	Used**	Region***	#	Name	Height* (m)	Used**	Region***
1	ASC1	91.0	no	ALSH	25	HNLC	6.1		PLNH
2	ANTG	82.4		ALNH	26	HOFN	17.3		AHNH
3	BRMU	22.2		AMNH	27	ISPA	116.9		PLSH
4	BDOS	9.38		ALNH	28	KOUC	23.6		PLSH
5	BARB	9.41		ALNH	29	KWJ1	8.4	no	PLNH
6	CCJM	160.0		PLNH	30	LHUE	32.04	no	PLNH
7	GUAM	146.6		PLNH	31	MAC1	13.4		PMSH
8	KERG	32.46		IMSH	32	MALD	4.9	no	ILNH
9	KOKB	1152.1		PLNH	33	MAUI	3045.0		PLNH
10	CHAT	47.3		PMSH	34	MKEA	3729.0		PLNH
11	COCO	4.0		ILSH	35	MAS1	154.8		ALNH
12	CRO1	12.8		ALNH	36	MCIL	10.8		PLNH
13	CNMR	10.7		PLNH	37	NOUM	22.8		PLSH
14	DGAR	9.12		ILSH	38	NYA1	47.0		AHNH
15	DOMI	24.2		ALNH	39	PDEL	54.1		AMNH
16	EISL	119.54	no	PLSH	40	PRMI	25.3		ALNH
17	FALE	13.2		PLSH	41	REYK	26.0		AHNH
18	GOUG	57.3	no	AMSH	42	REUN	1554.8		ILSH
19	GCFS	6.6		ALNH	43	SEY1	577.9		ILSH
20	GCGT	23.12		ALNH	44	SMRT	17.8		ALNH
21	GLPS	5.2		PLSH	45	TGCV	5.98		ALNH
22	GMSD	113.72		PMNH	46	THTI	91.1		PLSH
23	GTKO	14.9		ALNH	47	FALK	8.4		AMSH
24	HILO	10.6		PLNH					

*Above sea level.

**If station data was not used in this study due to missing collocations or poor time coverage.

***Ocean: Atlantic (A), Indic (I), Pacific (P). Latitudinal location (limits at 30^o and 60^o): low (L), middle (M) and high latitudes (H). Southern Hemisphere (SH), Northern Hemisphere (NH).

Table 2: GB stations and reanalyses where height differences stay above 200 m. Discrepancies are given in m with respect to the GB station height. No number implies difference below 200 m.

Atlantic (NH) station	ECMWF	NCEP
HOFN	427	309
REYK	218	229
Pacific (NH) station	ECMWF	NCEP
KOKB	-1130	-1192
HILO	552	-
MAUI	-2985	-2959
MKEA	-3166	-3637

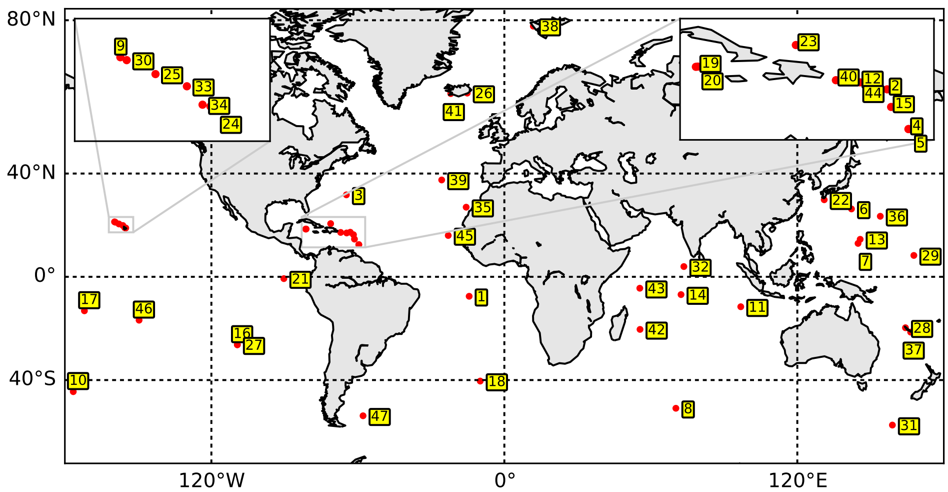

Figure 1: The 47 GB GNSS stations in small islands away from the continents.

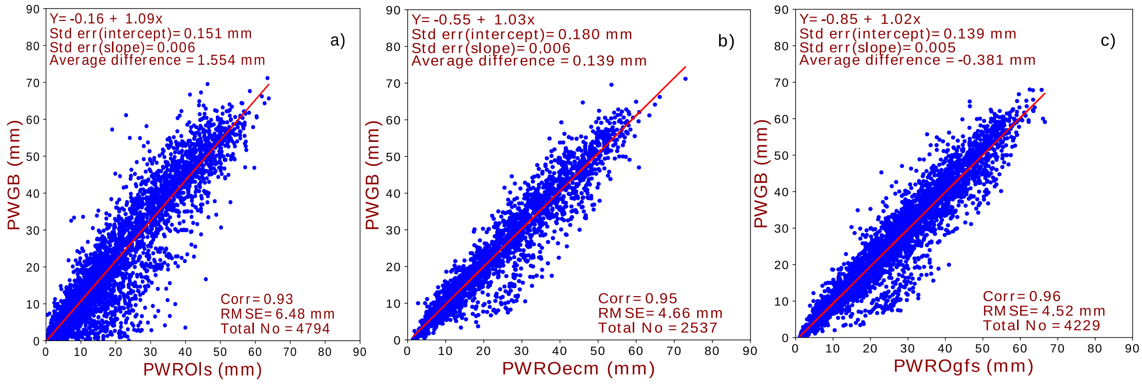

Figure 2: Scatterplot of collocated GPS RO and GB GNSS at 41 stations between years 2007 and 2014: a) PWROls, b) PWROecm, c) PWROgfs. The staright line indicates the linear regression in each panel. The RMS difference, correlation value, mean difference, the slope and intercept and their standard error and the number of pairs are given.

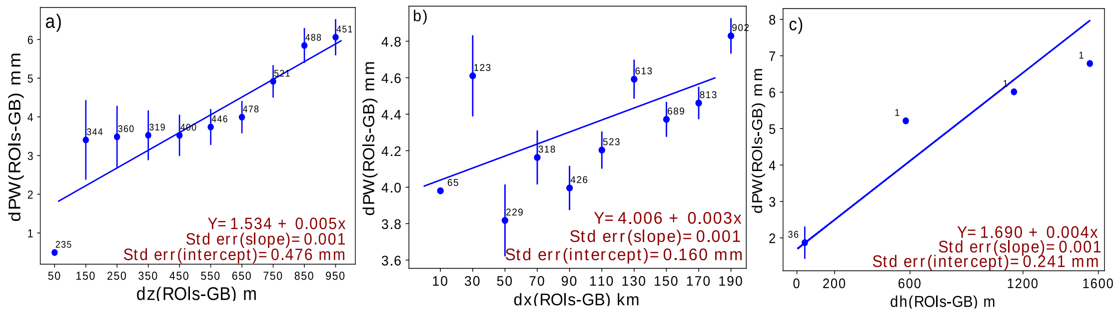

Figure 3: Absolute value of PW differences (dPW) between collocated GPS RO and GB GNSS in terms of a) height difference between station and the lowest RO measurement, b) horizontal separation and c) station height (39 sites). The blue dots represent the dPW mean in intervals of the horizontal axis and the line shows the best fit through them (all results are shown only for ROls as they are nearly identical for ROecm and ROgfs). The numbers besides the blue dots give the amount of averaged cases in the corresponding interval. Panels a) and b) have 10 uniform intervals (the distribution of station heights is rather clustered so it is not possible to repeat this procedure in the right panel). Vertical lines around each dot represent the standard deviation of the mean. The slopes have the following units: a) mm/m, b) mm/km, c) mm/m.

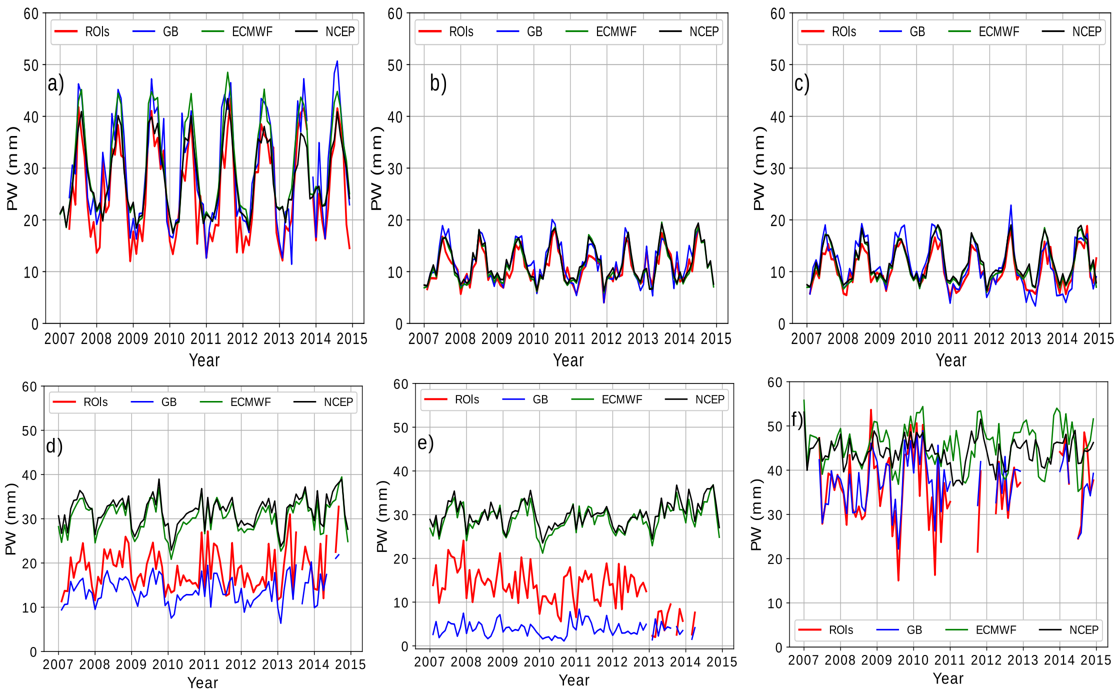

Figure 4: PW timeseries between years 2007 and 2014 for ROIs, GB and reanalyses for three stations that are below 30 m above sea level and three stations above 500 m: a) BMRU(22 m) b) HOFN(17 m) c) REYK(26 m), d) KOKB(1152 m) e) MAUI(3045 m) f) SEY1(577 m).

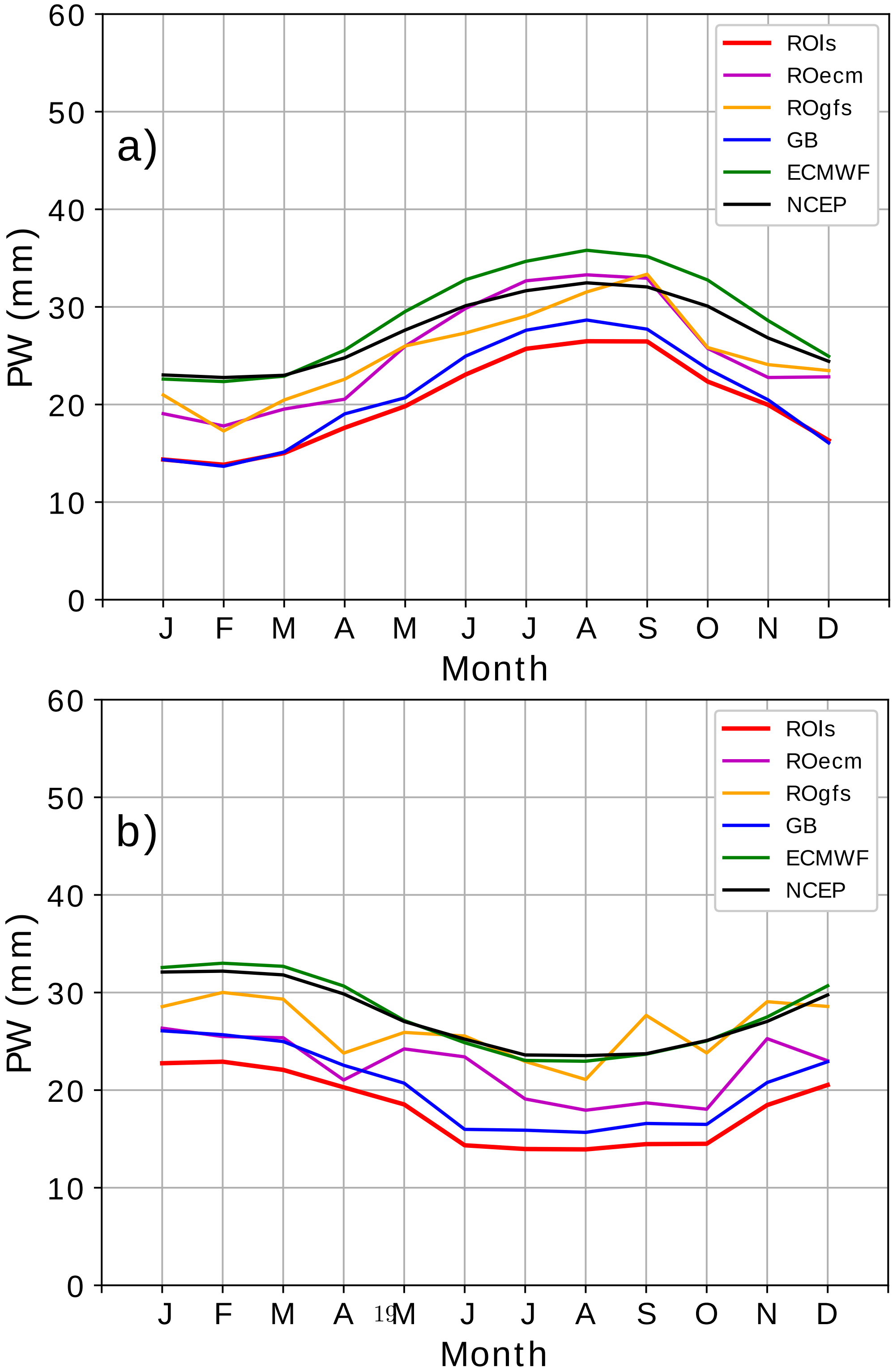

Figure 5: PW monthly mean between years 2007 and 2014 calculated at the collocations according to ROls, ROecm, Rogfs, GB GNSS and reanalyses from ECMWF and NCEP: a) Northern Hemispheres, b) Southern Hemisphere.

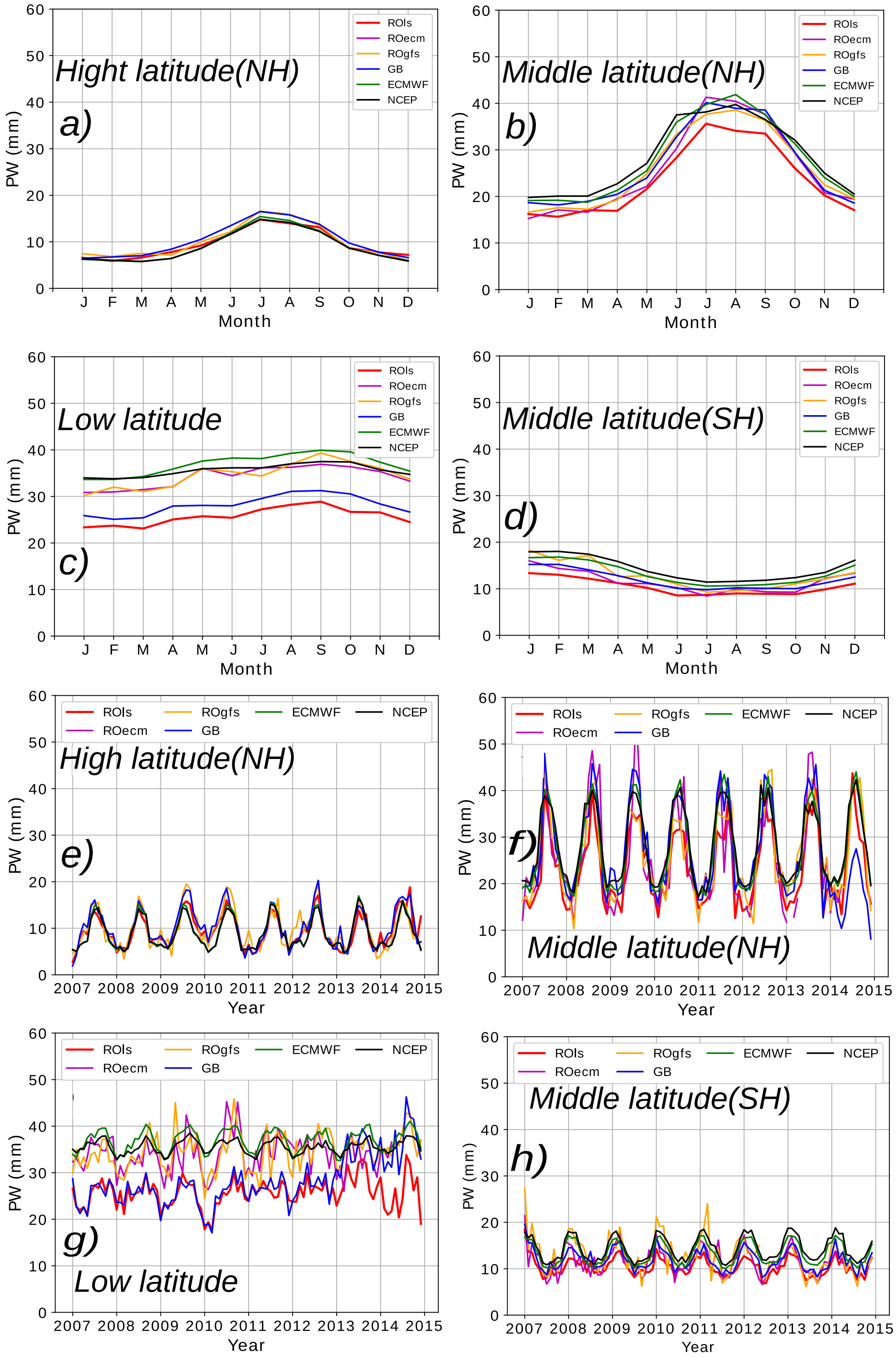

Figure 6: PW monthly mean in latitude bands between years 2007 and 2014 according to ROls, ROecm, Rogfs, GB GNSS and reanalyses from ECMWF and NCEP: a) High latitude (NH), b) Middle latitude (NH), c) Low latitude, d) Middle latitude (SH). Corresponding timeseries in e), f), g) and h).

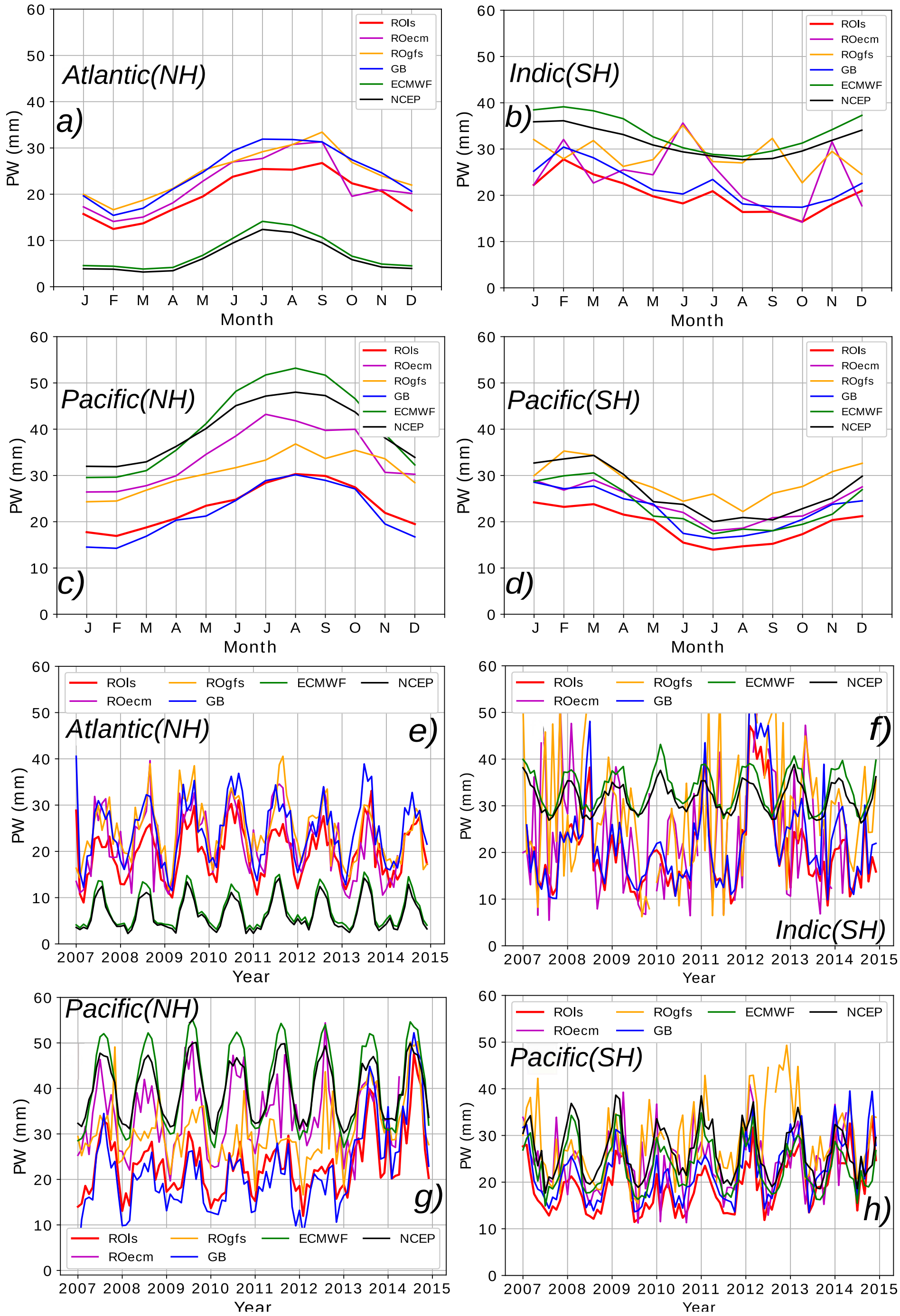

Figure 7: PW monthly mean above diverse oceans between years 2007 and 2014 according to ROls, ROecm, Rogfs, GB GNSS and reanalyses from ECMWF and NCEP: a) Atlantic (NH), b) Indic (SH), c) Pacific (NH), d) Pacific (SH). Corresponding timeseries in e), f), g) and h).

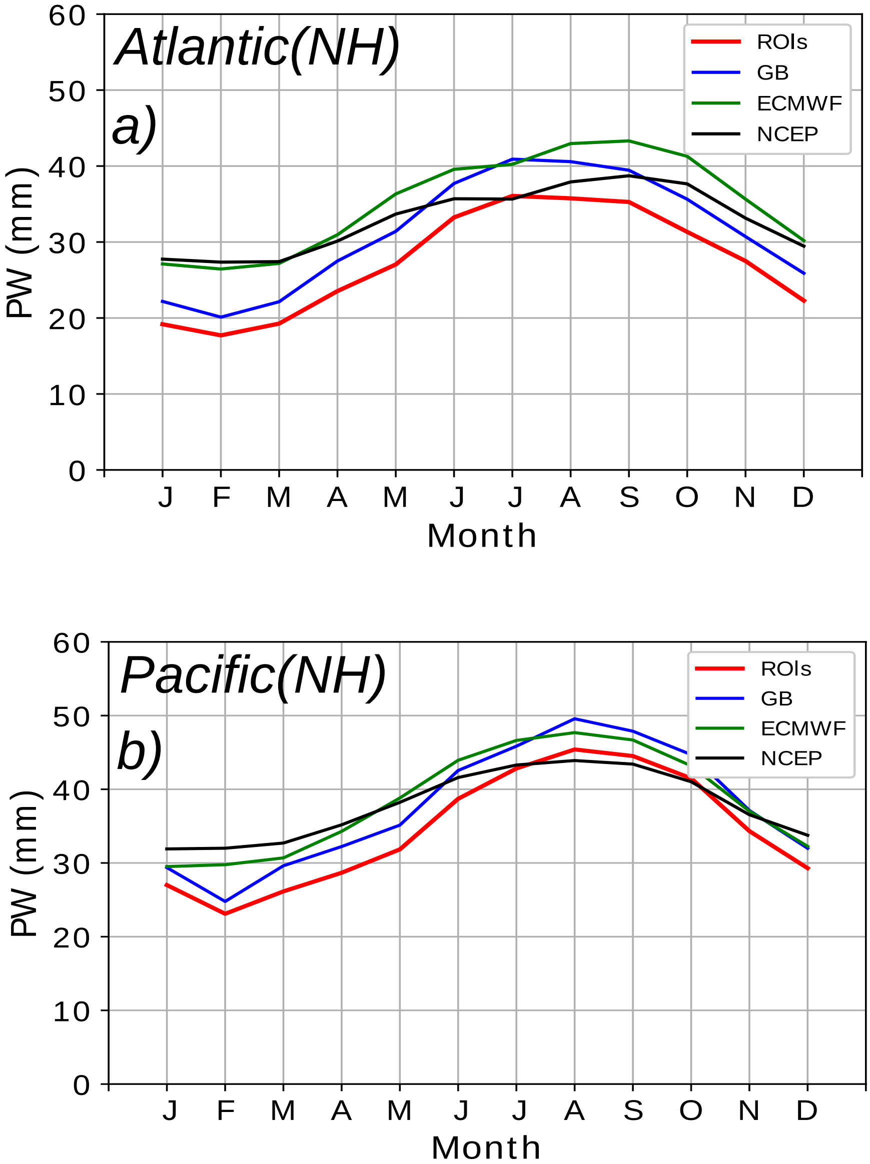

Figure 8: PW monthly mean between years 2007 and 2014 according to ROIs, GB GNSS and reanalyses from ECMWF and NCEP after removal of the places where the station heights and the models differ by more than 200 m: a) Atlantic (NH), b) Pacific (NH).

Highlights

- Diverse fillings in lowest levels of GPS RO may lead to significant differences in PW.
- RO and GB PW in oceanic areas have a mean difference of 1 mm and a 0.9 correlation.
- There is an intrinsic bias between PW obtained from RO and from GB methods.
- Reanalyses may not be capable of describing water vapor conditions in high islands.
- RO, GB and reanalyses PW show similar qualitative but different quantitative behavior.