Comparison of precipitable water via JRA-55 and GPS in Japan considering different elevations

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Abstract:

This study compared precipitable water vapor (PWV) of JRA-55 and GPS in Japan by considering different elevations in JRA-55 (geopotential height) and GPS (antenna height) because JRA-55’s PWV is pointed out to be underestimated as a result of dry bias in the middle and upper troposphere in the forecast model. We selected 26 grid points of JRA-55 over Japanese islands and the respective nearest 26 GPS stations operated by the Geospatial Information Authority of Japan. First, we linearly converted the geopotential height of 26 grid points to air pressure at the antenna height, assuming the sea surface and 1500-m height corresponding to 1013.25 hPa and 850 hPa, respectively. We then calculated JRA-55’s PWV by vertically integrating specific humidity in the pressure coordinate system using the antenna height from July 2010 through December 2012 (designated as “corrected PWV”). At 22 grid points among the 26, the geopotential height is higher than the antenna height, where the majority of the data of PWV provided by the JRA project was smaller than that retrieved from GPS. The underestimation of the corrected PWV decreased, although 65% of them remained underestimated. The underestimation of the corrected PWV increased in winter and decreased in summer.

KEYWORDS precipitable water; JRA-55; Global Positioning System (GPS); geopotential height; antenna height; height correction

INTRODUCTION

Precipitable water vapor (PWV) is total water vapor that is contained from ground surface to the top of the atmosphere. It is one of the essential components of the hydrological cycle. To calculate PWV, radiosonde data have long been used, and they are still valid for this purpose. Since the 1990s, observational data of Global Positioning Systems (GPS) have been used to estimate PWV (e.g. Bevis et al., 1992). In principle, GPS is used to determine a three-dimensional position by receiving radio signals from GPS satellites. Such signals are, however, delayed by the atmosphere near the ground surface. Part of that delay can be attributed to PWV, therefore, PWV can be inferred from GPS observations. In fact, such studies have been reported in the mid-1990s (e.g. Bevis et al., 1994; Businger et al., 1996; Duan et al., 1996; Ware et al., 1996).

Additionally, one can calculate PWV using a global atmospheric reanalysis dataset such as JRA-55 (Kobayashi et al., 2015; Harada et al., 2016). For instance, Trenberth et al. (2011) compared the global atmospheric water budget using eight reanalyses. In comparison with Trenberth et al. (2011), Harada et al. (2014) pointed out that the global average of PWV calculated using JRA-55 was the smallest among the eight reanalyses. As a possible reason for this underestimation, Harada et al. (2014) identified that dry bias in the middle and upper troposphere in the forecast model of JRA-55 is responsible for it: the model cannot retain water vapor supplied by observational data. That vapor is promptly removed from the atmosphere as precipitation.

However, the relation between PWV as assessed by JRA-55 and GPS in Japan has not yet been investigated. In particular, actual topography and geopotential height of JRA-55 are considerably different (Figure 1), so that for comparing PWV of JRA-55 and GPS in Japan, the correction of surface topography is necessary. Because radiosonde data are incorporated into JRA-55 through 4-dimensional variational data assimilation (4DVAR), we used GPS-retrieved PWV, independent of 4DVAR, to confirm the characteristics of PWV via JRA-55.

DATA

GPS-retrieved PWV

We used GPS-retrieved PWV from July 2010 through December 2012. During this period, heavy rainfall events such as “Northern Kyushu heavy rainfall in July 2012” (Manda et al., 2014) occurred which we will investigate in the future. PWV was calculated using observational data at 1,300 GPS stations operated by the Geospatial Information Authority of Japan (GSI), by applying the GIPSY-OASIS II software (Webb and Zumberge, 1993). The data are available for every 5 min.

Regarding the accuracy of GPS-retrieved PWV in Japan, Nishimura et al. (2003) investigated this aspect on a seasonal basis from January to December 2000 using GIPSY-
Figure 1. (a) Geopotential height around Japan in JRA-55. (b) Actual topography (SRTM30_PLUS, about 1 km resolution, Becker et al., 2009) and spatial distribution of 26 GPS stations at the nearest grid points of JRA-55 over the Japanese islands: numbers correspond to those presented in Table I. Italic with underlined IDs are four stations where the antenna height of GPS is higher than the geopotential height of JRA-55.

OASIS II. They compared 14 radiosonde stations’ PWV with GPS-retrieved ones. As a result, the bias between GPS-retrieved PWV and that of the radiosonde was almost 0 mm, and the root mean square error (RMSE) of their difference was 2.3 mm. They also showed that the difference between PWV obtained via radiosonde and that from GPS was almost within 2.3 mm throughout the year although only the results from three stations were presented.

Shoji (2009, 2015) also evaluated the accuracy of recent GPS-retrieved PWV in Japan using GIPSYS-OASYS II, however, these studies did not mention the seasonal variation of the accuracy. We therefore set ±2.3 mm, shown by Nishimura et al. (2003), as unavoidable error of GPS-retrieved PWV. Namely, if the absolute value of the difference between GPS-retrieved PWV and JRA-55’s one was larger than 2.3 mm, we regarded the difference as signal. We used such data for calculating “underestimation ratio” as explained in METHODS.

**PWV assessed by JRA-55**

We also used the PWV estimated by the JRA project (JMA, 2013, hereinafter, “JRA-55’s original PWV”). The spatial resolution was 1.25° × 1.25°, and the temporal resolution was 6 h (00Z, 06Z, 12Z, 18Z). In JRA-55, atmospheric data at 37 levels are available from 1,000 hPa to 1 hPa, whereas specific humidity is available for 27 levels up to 100 hPa.

For this study, aside from JRA-55’s original PWV, we also calculated PWV through JRA-55 using specific humidity from the ground surface to 100 hPa (hereinafter, “JRA-55’s corrected PWV”). The calculation was performed because the surface elevation adopted in the forecast model of JRA-55 (Figure 1a) differs from the actual elevation (antenna height of GPS, see Table I). The surface elevation of JRA-55 was calculated by dividing the geopotential of JMA (2013) by gravitational acceleration. By comparing JRA-55’s original and corrected PWVs, we can consider the effect of height correction.

**Precipitations of JRA-55 and AMeDAS**

In RESULTS, we present discussion on the hydrological cycle of JRA-55. To support that discussion, we compared the forecast precipitation of JRA-55 and observed precipitation at the Automated Meteorological Data Acquisition System (AMeDAS) operated by JMA. About 1,300 stations of AMeDAS cover the Japanese islands. The forecast precipitation of JRA-55 is available every 6 hr through JMA (2013), whereas the observed precipitation at AMeDAS is available every 1 hr through JMA (2019). Monthly precipitation data are available both in JRA-55 and AMeDAS, which were used for the analysis.

**METHODS**

First we selected grid points of JRA-55 over Japanese islands using actual topography. For the selected 26 grid points, we assigned the nearest respective GPS stations (Figure 1b and Table I).

Next, we converted geopotential height of JRA-55 at 26 grid points to antenna height of GPS (Table I), assuming the linear relationship between pressure (hPa) and elevation (m), i.e., sea surface and 1500-m height corresponding to 1013.25 hPa and 850 hPa, respectively. At 22 grid points, the geopotential height is higher than the antenna height (Table I), while at the remaining 4 grid points, the antenna height is greater.

We calculated JRA-55’s corrected PWV by vertically integrating specific humidity from the ground surface to 100 hPa (Equation 1) as

\[ W = \frac{1}{g} \int_{p_s}^{100} q \, dp, \]

where \( W \) stands for PWV (mm, presuming 1,000 kg/m³ as the water density), \( g \) denotes gravitational acceleration (9.81 m/s²), \( p_s \) represents the surface pressure (hPa), and \( q \) signifies specific humidity (kg/kg). Specific humidity at the ground surface was extrapolated linearly using the data obtained for the nearest two designated levels above the ground surface.
Table I. General information related to 26 grid points of JRA-55 over the Japanese islands and respective nearest GPS and AMeDAS stations. Italic with underlined characters and IDs of the column of GPS represent the stations where the antenna height of GPS is higher than the geopotential height of JRA-55

| JRA-55 | GPS | AMeDAS |
|--------|-----|--------|
| Latitude (°) | Longitude (°) | Geopotential height (m) | Station’s ID | Station’s name | Latitude (°) | Longitude (°) | Antenna height (m) | Station’s name | Latitude (°) | Longitude (°) |
| 42.50 | 140.00 | 99.24 | 0017 | Setana | 42.45073633 | 139.85766703 | 41.00 | Imakane | 42.4283 | 140.0083 |
| 41.25 | 141.25 | 75.08 | 0024 | Mutsu | 41.30077019 | 141.21327717 | 23.68 | Mutsu | 41.2833 | 141.2100 |
| 36.25 | 136.25 | 223.50 | 0055 | Mikuni | 36.23117358 | 136.17297394 | 26.79 | Mikuni | 36.2433 | 136.1733 |
| 45.00 | 142.50 | 91.50 | 0103 | Esashi | 45.00239956 | 142.53708717 | 15.33 | Kitamiesashi | 44.9400 | 142.5850 |
| 43.75 | 143.75 | 310.56 | 0114 | Kitami | 43.84889878 | 143.78255722 | 175.49 | Sakaino | 43.7067 | 143.6433 |
| 42.50 | 141.25 | 145.01 | 0139 | Shiraoi | 42.54980242 | 141.36147769 | 10.63 | Shiraoi | 42.5433 | 141.3517 |
| 40.00 | 141.25 | 333.70 | 0161 | Iwate | 39.98056617 | 141.22507700 | 273.04 | Okunakayama | 40.0600 | 141.2250 |
| 38.75 | 140.00 | 274.17 | 0195 | Tachikawa | 38.75971661 | 139.95738953 | 21.04 | Karikawa | 38.8000 | 139.9733 |
| 37.50 | 140.00 | 508.42 | 0302 | Inawashiro1 | 37.56894639 | 140.07269742 | 632.41 | Wakamatsu | 37.4883 | 139.9100 |
| 35.00 | 136.25 | 243.38 | 0323 | Minakuchi | 34.98635333 | 136.14503275 | 179.10 | Tsuchiyama | 34.9383 | 136.2783 |
| 35.00 | 133.75 | 257.55 | 0329 | Ochiai | 35.00296247 | 133.73449894 | 135.85 | Ashinishi | 34.9617 | 133.8117 |
| 43.75 | 142.50 | 419.53 | 0508 | Asahikawa | 43.73852608 | 142.40960708 | 144.12 | Higashikawa | 43.7017 | 142.5083 |
| 36.25 | 140.00 | 206.99 | 0582 | Shimodate | 36.30070503 | 139.98777467 | 34.94 | Shimodate | 36.2817 | 139.9883 |
| 36.25 | 137.50 | 875.39 | 0618 | Kamitakara | 36.28564322 | 137.36302100 | 634.37 | Tchoji | 36.2483 | 137.5033 |
| 35.00 | 135.00 | 194.86 | 0649 | Takino | 34.93619011 | 134.94503164 | 64.15 | Nishiwaki | 34.9983 | 134.9967 |
| 32.50 | 130.00 | 97.71 | 0774 | Reihoku | 32.52453556 | 130.08518406 | 27.71 | Hondo | 32.4683 | 130.1800 |
| 43.75 | 141.25 | 112.70 | 0785 | Hamamasu | 43.62433139 | 141.37058078 | 20.94 | Hamamasu | 43.5817 | 141.3867 |
| 37.50 | 138.75 | 321.47 | 0807 | Niigata Mishima | 37.49865597 | 138.77984767 | 61.70 | Nagaoka | 37.4500 | 138.8233 |
| 43.75 | 145.00 | 83.65 | 0864 | Shibetsu2 | 43.7902933 | 145.05686144 | 12.62 | Itokushibetsu | 43.7217 | 144.9883 |
| 42.50 | 142.50 | 241.24 | 0890 | Monbetsu2 | 42.5526450 | 142.3952133 | 129.42 | Sasayama | 42.4333 | 142.4817 |
| 38.75 | 141.25 | 199.85 | 0914 | Miyagi Towa | 38.74320556 | 141.31790875 | 16.43 | Yoneyama | 38.6267 | 141.1883 |
| 40.00 | 140.00 | 148.78 | 0923 | Hachiyu | 40.09969561 | 140.00550350 | 8.61 | Oogata | 40.0000 | 139.9500 |
| 36.25 | 138.75 | 823.10 | 0957 | Nannmoku | 36.20026647 | 138.70298806 | 616.89 | Nishinomaki | 36.2450 | 138.7067 |
| 35.00 | 132.50 | 218.00 | 0923 | Yushu | 35.03190261 | 132.38556256 | 272.44 | Kawamoto | 34.9767 | 132.4917 |
| 32.50 | 131.25 | 327.48 | 0983 | Monbetsuka | 32.52793367 | 131.36470317 | 836.25 | Morotsuka | 32.5167 | 131.3350 |
| 35.00 | 137.50 | 372.13 | 1003 | Tsukide | 34.96748200 | 137.42331356 | 539.33 | Tsukide | 34.9767 | 137.4250 |
(Oki et al., 1995) to avoid the use of data under the ground. Calculations were performed 4 times a day from July 2010 through December 2012. For the same period, we also selected JRA-55’s original PWV at 26 grid points provided by JMA (2013).

Concerning GPS-retrieved PWV, we calculated 30-min averages before each of 00, 06, 12, and 18Z following Nishimura et al. (2003), because radiosonde is usually released at the ground 30 min before 00Z and 12Z in Japan. To calculate 30-min averages using 5-min data, we allowed only one missing of six data of GPS-retrieved PWV.

Using these PWV obtained via these three approaches, we compared JRA-55’s original/corrected PWV and GPS-retrieved value, and investigated the seasonal variations in their characteristics. All data were compiled by months/years. We counted underestimated data of JRA-55’s original/corrected PWV to GPS-retrieved one using 6-hourly data, and divided the number by all observations in a month. Here, we define it as “the underestimation ratio”. For this comparison, we only considered underestimation greater than 2.3 mm.

Regarding the observed precipitation, we did not use monthly precipitation at AMeDAS with any missing data. This procedure did not affect the following results qualitatively.

**RESULTS**

**Example of a scatter diagram and time series**

Figures 2a–d depict scatter diagrams between GPS-retrieved PWV and that of JRA-55 at Setana, northern Japan (ID 0017 in Table I). The antenna height at this station is 41.00 m, whereas the geopotential height is 99.24 m (Table I).

In January 2011, PWV is small, and the data are concentrated in 0–10 mm (Figures 2a and 2b). In these figures, the majority of the data of JRA-55’s original PWV (Figure 2a) and the corrected PWV (Figure 2b) underestimate the GPS-retrieved one. Contrarily, PWV varies between 10 mm and ca. 60 mm in July, 2011 (Figures 2c and 2d). In Figure 2c, many data of JRA-55’s original PWV underestimate the GPS-retrieved one, whereas the underestimation is fairly improved in the corrected PWV (Figure 2d). In Figures 2a–d, the correlation coefficient is respectively shown, however, the difference of the correlation coefficient before and after height correction is trivial in each season.

This improvement was apparent when we investigated seasonal variation. We conducted similar analyses for other months/years and compiled the data accordingly (Figures 2a–2d). Figure 2e shows the seasonal variation in the underestimation ratio of JRA-55’s PWV to the GPS-retrieved one. The blue line represents JRA-55’s original PWV, whereas the red line represents the corrected one. For each month, the JRA-55’s original PWV is greater than or equal to the corrected one, as evidenced by the positioning of the blue and red lines. Especially, the underestimation ratio decreases in summer over three years, which is apparently affected by correcting the elevation (Figure 2e). However, more than 40% of JRA-55’s corrected PWV still underestimates the GPS-retrieved value in summer (Figure 2e).

**Seasonal variation in the underestimation ratio at 26 grid points/stations in Japan**

We performed similar analyses to those detailed in the previous section at 25 other stations. Because 26 stations were classified into two groups, i.e. antenna height of GPS is lower than geopotential height of JRA-55 (22 stations) and vice versa (4 stations, Table I), we compiled the results of these two groups separately.

Figure 3a displays the underestimation ratio of JRA-55’s original PWV to GPS-retrieved one. The blue line shows the case of the 22 stations above. As expected, the majority
Figure 3. (a) Seasonal variation in the underestimation ratio of JRA-55’s original PWV to the GPS-retrieved one. The orange/blue line shows the case of stations where the antenna height of GPS is higher/lower than the geopotential height of JRA-55; respective standard deviations are also shown. (b) Same as (a) but for JRA-55’s corrected PWV.

Figure 4a presents the spatial distribution of the underestimation ratio of JRA-55’s original PWV to the GPS-retrieved one because water vapor is concentrated in the lower troposphere. Contrarily, the orange line in Figure 3a represents distinct seasonal variation, i.e. the underestimation ratio declines in summer and increases in winter. This characteristic also reflects the different elevations of JRA-55 and GPS. The difference between blue and orange lines in Figure 3a is statistically significant at the 5% level by Welch’s test (Welch, 1947).

Figure 3b depicts the case for JRA-55’s corrected PWV. By height correction, the underestimation ratio of the 22 stations (blue line) considerably decreases, especially in summer. In contrast, the underestimation ratio of the 4 stations (orange line) increases in summer (Figure 3b). Broadly speaking, the significant difference between blue and orange lines in Figure 3a is minimized in Figure 3b by correcting the elevation. The difference between blue and orange lines in Figure 3b was not statistically significant at the 5% level by Welch’s test. For both lines, the underestimation ratio is larger in winter and smaller in summer, i.e. PWV is abundant in summer, implying the intensification of the hydrological cycle in summer as per JRA-55.

Spatial distribution of the underestimation ratio in Japan

Figure 4a presents the spatial distribution of the underestimation ratio of JRA-55’s original PWV to GPS-retrieved one in January 2012. In this figure, ca. 100% of the underestimation ratio is observed in most GPS stations except Morotsuka in southern Japan (ID 1083 in Figure 4). This characteristic appears clearer if one corrects the difference in the elevation (Figure 4b).

In July 2012 with abundant PWV, the underestimation ratio decreases at the majority of stations after correcting the elevation (Figures 4c and 4d). In this regard, Morotsuka, Tsukide in central Japan (ID 1103), and Inawashiro 1 in northern Japan (ID 0202) are exceptions. At these stations, the antenna height is higher than the geopotential height. The effects of height correction at these stations are depicted as an orange line in Figure 3.

In Figure 4, Morotsuka shows peculiar change both in January and July 2012 after height correction. In both months, the underestimation ratio fairly increases (Figure 5). Among all GPS stations listed in Table I, the difference of the elevation between antenna height and geopotential height is the greatest in Morotsuka. Figures 5a and 5b present effects of the correction in January 2011, whereas Figures 5c and 5d show the case in July 2011. In comparison with Figure 2e, the blue line in Figure 5e displays peculiar seasonal variation. The underestimation ratio of JRA-55’s original PWV to the GPS-retrieved one is nearly equal to zero in summer although it fairly increases in other seasons. This characteristic has, in part, been portrayed in Figure 4.

Relation between seasonal variation of the underestimation ratio of JRA-55’s PWV and precipitation at 26 grid points/stations

In Figure 3b, the underestimation ratio of JRA-55’s corrected PWV is larger in winter and smaller in summer. In summer, the atmosphere is relatively wetter than in winter; it holds more PWV. Therefore, precipitation in summer is expected to be less than in other seasons. We investigated JRA-55’s precipitation from this perspective.

Figure S1 shows seasonal variation of the ratio of JRA-55’s precipitation to AMeDAS’s one (hereinafter, “precipitation ratio”). Spatial averages and standard deviations at 26 grid points/stations over Japanese islands are shown. The annual mean of the precipitation ratio in Figure S1 is 1.37, i.e. JRA-55 generally overestimates AMeDAS’s precipitation at these grid points/stations. The seasonal variation is small in Figure S1, however, the precipitation ratio tends to be larger in winter and smaller in other seasons. As shown in Figure S1, the standard deviation among the 26 grid points/stations is also larger in winter, which will be attributable to the underestimation of the observed solid precipitation at AMeDAS.

One peculiar characteristic of Figure S1 is the large standard deviation depicted in January 2011. A large precipitation ratio is observed at Shiraoi (26.47), Nishiwaki (9.84), Asahinishi (7.97), and Yoneyama (6.79) in Table I. Why such large precipitation ratios are concentrated in January 2011 remains unknown. However, Figure S1 displays that JRA-55’s precipitation is generally greater than AMeDAS’s precipitation throughout the year, i.e. precipitation in summer is not less than in other seasons at least at 26 grid points over the Japanese islands.
RESULTS revealed that more than 65% of JRA-55’s corrected PWV still underestimated GPS-retrieved one (blue line in Figure 3b). We conclude that JRA-55’s PWV tends to underestimate the GPS-retrieved one, even after we performed the elevation correction. A possible reason is the dry bias in the middle and upper troposphere of the forecast model adopted in JRA-55 (Harada et al., 2014; Kobayashi et al., 2015).

Kobayashi et al. (2015) presented a time–height cross-section for global mean monthly specific humidity increments of JRA-55, showing that the forecast model used in JRA-55 has dry bias in the middle and upper troposphere above 850 hPa. Although this is the global mean, the geographical distribution of PWV increments averaged over 2002–2008 is also depicted in Kobayashi et al. (2015). In the figure, the dry bias area extends spatially from the northwestern equatorial Pacific to Japan, i.e. the dry bias in the middle and upper troposphere is mainly derived from the regions of deep convection within which Japan is included. It is possible that underestimation of the JRA-55’s PWV compared to the GPS-retrieved one is attributable to this characteristic.

Actually, PWV is a vertically integrated variable. Therefore, this study cannot investigate the vertical distribution of humidity in the atmosphere. However, even after correcting the elevation, JRA-55’s PWV still underestimated the GPS-retrieved one. In relation to these characteristics, JRA-55’s precipitation overestimated the observed precipitation around 26 grid points over the Japanese islands (Figure S1). It does not contradict results reported by Harada et al. (2014) who pointed out that the forecast model of JRA-55 cannot retain the water vapor supplied by observational data. The vapor is removed promptly from the atmosphere as precipitation, i.e. dry bias in the middle and upper troposphere in JRA-55 is a candidate for underestimation of PWV.

CONCLUSIONS

This study compared JRA-55’s PWV and GPS-retrieved one in Japan by considering their different elevations. We selected 26 grid points throughout the Japanese islands of JRA-55 and the nearest respective 26 GPS stations, and calculated PWV four times a day from July 2010 through
December 2012. At 22 grid points among the 26, the geopotential height of JRA-55 was higher than the antenna height of GPS, where most of JRA-55’s PWV was smaller than the GPS-retrieved one. After correcting the geopotential height to the antenna height at 26 grid points, the underestimation was less, although more than 65% of JRA-55’s corrected PWV remained underestimated. Regarding seasonal variation, the underestimation of JRA-55’s corrected PWV increased in winter and decreased in summer.

As a possible reason for the underestimation of JRA-55’s PWV, we can infer dry bias at the middle and upper troposphere of the forecast model adopted in JRA-55. To elucidate this point, further analysis of the JRA-55’s hydrological cycle should be done to clarify the reasons and mechanisms.

**ACKNOWLEDGMENTS**

We are indebted to the Observational Division, Observational Department of JMA for analyzing GPS-retrieved PWV. It was calculated using observational data at GPS stations operated by GSI, by applying the GIPSY-OASIS II software developed at the California Institute of Technology, U.S.A. JRA-55 datasets were provided by JMA. Assistance by all personnel and institutions is greatly appreciated.

**SUPPLEMENTS**

Figure S1. Seasonal variation of the ratio of JRA-55’s precipitation to the nearest AMeDAS’s precipitation from July 2010 through December 2012. Spatial average and standard deviation of 26 grid points/stations over the Japanese islands are also shown. The horizontal dashed line shows that precipitation ratio is 1.0

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