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Analysis on Characteristics of Radiosonde Bias Using GPS Precipitable Water Vapor

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As an observation instrument of the longest record of tropospheric water vapor, radiosonde data provide upper-air pressure (geopotential height), temperature, humidity and wind. However, the data have some well-known elements related to inaccuracy. In this article, radiosonde precipitable water vapor (PWV) at Sokcho observatory was compared with global positioning system (GPS) PWV during each summertime of year 2007 and 2008 and the biases were calculated. As a result, the mean bias showed negative values regardless of the rainfall occurrence. In addition, on the basis of GPS PWV, the maximum root mean square error (RMSE) was 5.67 mm over the radiosonde PWV.

Keywords: GPS, precipitable water vapor, radiosonde, bias

1. INTRODUCTION

Precipitable water vapor (PWV) is highly variable and plays an important role in meterological phenomena in various time-space scales. Water vapor is also a greenhouse gas that affects the global climate system and it is involved in the formation of cloud and aerosol as well as chemical composition of the lower atmosphere. The time-space distribution of water vapor and the accuracy limit of the observation affect the weather forecast, sometimes resulting in failure in short-term forecast, especially the precipitation forecast.

To improve the ability to predict precipitation for weather forecast, it is important to understand the space-time distribution of PWV by means of high-accuracy observation. The PWV observation methods in Korea at present include radiosonde, microwave radiometer and remote sensing using satellite.

Among these observation methods, radiosonde, which currently provides the longest period of record of the tropospheric PWV as a single observation instrument (Durre et al. 2009), has high vertical resolution and the data of more than 60 years over a global, extensive area are available. Radiosonde is the observation instrument that produces the vertical data of air pressure (geopotential height), air temperature, relative humidity and wind 2 to 4 times a day as it rises up from the ground surface to the atmosphere. The produced data is utilized as the numerical data for the weather forecast as well as for various studies including model verification, climate research and satellite data verification (Kim et al. 2009).

Although radiosonde has been one of the main observation tools for measuring PWV since the past, it has error and bias that are unique to the sensor and it tends to measure the relative humidity as lower than the actual value, resulting in underestimation of the precipitation in numerical models (Lorenc et al. 1996). It has been also known that the time resolution is mostly limited to 2 times per day and the accuracys of temperature and relative humidity are only about 0.2 °C and 3.5 %, respectively, in general (Elliot & Gaffen 1991). Due to these, the PWV values derived from the radiosonde data inherently

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include error in the range of 5-10% (Motell et al. 2002).

In the previous studies regarding the error and bias, it was shown that the dry bias of radiosonde is greatly affected by the solar radiation (Wang et al. 2002) and the main factors of the radiosonde bias are the atmospheric relative humidity and the solar radiation depending on the elevation (Wang & Zhang 2008). In addition, Kwon et al. (2007) showed that there was a dry bias in radiosonde when compared with GPS and the difference of the PWV between the two increased especially in daytime.

GPS PWV is derived by the inversely calculating the delay that takes place as the signal emitted from a GPS satellite is refracted before it arrives at the ground station. The advantages of the GPS-based meterological information are that the observation is always possible, 24 hours a day, and the data with high time-space resolution can be obtained since the distribution can be dense in proportion to the number of installed ground stations. Additionally, it has been known that the accuracy level of the PWV derived from GPS signals is almost equal to that of radiometer or radiosonde (Bevis et al. 1992, 1996, Rocken et al. 1995, Businger et al. 1996, Duan et al. 1996). Currently, Korea Astronomy and Space Science Institute (KASI) produces GPS PWV data in 10-minute time resolution using the constant GPS observation network data. Through the data, a small time-scale change in the atmosphere can be detected and the fine time resolution is an advantage of GPS observation when compared with the conventional radiosonde observation.

Nakamura et al. (2004) stated that the accuracy of the PWV derived by the newest GPS analysis technology was equivalent to or even higher than that of the radiosonde. Wang & Zhang (2008) mentioned that, although radiosonde humidity data is used for the assessment of GPS PWV accuracy, radiosonde data is usually the source of error when the two data are inconsistent with each other and they established the GPS PWV as the reference for the comparison of the PWV data from the two different observation, emphasizing that the radiosonde and GPS observation should be carried out at one location for more distinctive comparison. Takiguchi et al. (2000) assumed that the difference between the PWV from GPS and radiosonde might be mostly because of the radiosonde and presented the PWV estimation results, having GPS as the reference.

Most of the domestic and international studies with respect to the comparison of the PWV derived from GPS and radiosonde have been focused on the monthly, seasonal and yearly analysis and only a few studies directly compared the radiosonde PWV with the GPS PWV, case by case, considering whether there was precipitation or not. The comparative analysis considering actual precipitation can provide guidance for the improvement of the radiosonde humidity sensor accuracy.

In this study, we compared the PWV derived from the radiosonde observation of the Sokcho meteorological observatory with the PWV from the Sokcho GPS observatory provided by KASI. Through this comparison, we examined the characteristics of the radiosonde PWV observation data depending on the precipitation. In this article, GPS and radiosonde are firstly introduced and then the comparative analysis of the PWV data from the two observation instruments is described.

2. OBSERVATION DATA AND METHODS OF STUDY

2.1 GPS and radiosonde

GPS signal is delayed as it passes through the troposphere of the atmosphere and the signal delay is divided into dry delay and wet delay. Dry delay is caused by oxygen, nitrogen and carbon dioxide, while wet delay is caused by water vapor.

Zenith total delay (ZTD) can be divided into two part: zenith hydrostatic delay (ZHD) by dry air and zenith wet delay (ZWD) by water vapor (Song et al. 2002).

$$\begin{aligned} ZTD &= \tau_h m_h(\varepsilon) + \tau_w m_w(\varepsilon) \\ &= ZHD + ZWD \end{aligned} \tag{1}$$

In Eq. (1) τ denotes the dry delay and wet delay, and m_h and m_w respectively denote the dry and wet mapping functions depending on the elevation, ε (Niell 1996). ZTD is calculated by the data processing and ZHD can be calculated with the experimental model and the air pressure at the observatory. Based on these, ZWD can be derived. ZHD is calculated using the meteorological observation data as in the Eq. (2) (Elgered et al. 1991).

$$ZHD = (2.2779 \pm 0.0024)P_0 / (1 - 0.00266\cos 2\phi - 0.00028H) \tag{2}$$

Here, P_0 denotes the air pressure at the observation position (hPa) and ϕ and H are the latitude (rad) and altitude (km) of the observation position, respectively. integrated water vapor (IWV) per unit area is expressed as in the Eq. (3) (Bevis et al. 1992).

$$IWV = \kappa \cdot ZWD \tag{3}$$

where κ is defined as in the Eq. (4)

$$\frac{1}{\kappa} = 10^{-6}\left(\frac{k_3}{T_m} + k'_2\right)R_v \tag{4}$$

Here, R_v denotes the gas constant of water vapor, k'_2 = (17±10) K·hPa^{-1}, k_3 = (3.776±0.004) x 10^5 K^2·hPa^{-1} and T_m is the mean temperature of the air column. In Eq. (4) the effect of k'_2 and k_3 error on the resulting values is less than 2%.

Bevis et al. (1992) showed that κ can be determined from the surface temperature in 2% of the relative RMSE and the error of IWV derived from ZWD is within the range of 4% even though the error of T_m may be large. The method to determine T_m is shown in Eq. (5) (Davis et al. 1985).

$$\int dz \frac{P_w}{T} = T_m \int dz \frac{P_w}{T^2} \qquad (5)$$

where P_w is the vapor pressure at the observation position and T is the surface temperature. PWV can be obtained by dividing the IWV derived from Eq. (3) with density of water (ρ) as follows:

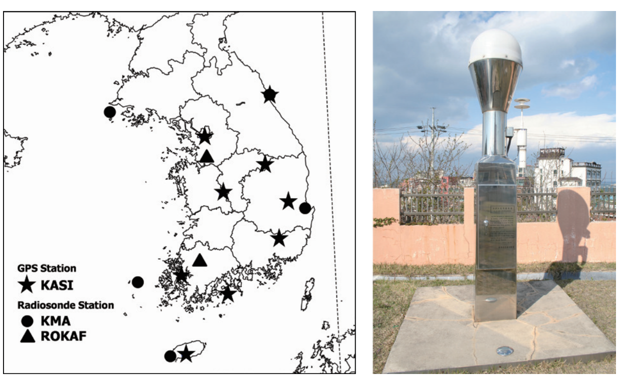

Fig. 1. (Left) The locations of GPS and radiosonde (KASI: Korea Astronomy and Space Science Institute, KMA: Korea Meteorological Administration, ROKAF: Republic of Korea Air Force), (Right) GPS station at Sokcho.

$$PWV = \frac{IWV}{\rho} \qquad (6)$$

PWV was derived in 30-minute interval using the meteorological data observed with MET3A which is the meteorological sensor attached to the GPS observation tower. The GPS data processing was conducted with Bernese 5.0 developed in University of Bern, Switzerland (Dach et al. 2007).

Among the 9 constant GPS observatories operated by KASI, Sokcho observatory performs radiosonde and GPS observation at the same area. Thus, the results can be directly compared excluding the spatial error that may take place when the observation locations are different.

Fig. 1 shows the geographical distribution of the GPS and radiosonde observatories and the GPS observatory located in Sokcho. The nine GPS observatories are located in Daejeon (DAEJ), Mokpo (MKPO), Sokcho (SKCH), Seoul (SKMA), Jeju (JEJU), Mt. Bohyeon (BHAO), Mt. Sobaek (SBAO) and Goheung (KOHG) (observatory codes in parenthesis). The observatory operated in Yeosu (YOSU) was transported to Goheung (KOHG) in early 2008. Radiosonde observation is operated currently in 5 locations including Sokcho (47090), Baekryeongdo (47102), Pohang (47138), Heuksando (47169) and Jeju (47185) by the Korea Meteorological Administration and in Osan (47122) and Gwangju (47158) by the Air Force. The numbers in the parenthesis are the observatory numbers of the observatories designated by World Meteorological Organization (WMO).

The data of University of Wyoming opened on the website (http://weather.uwyo.deu /upperair/soundin.html) were used for the radiosonde PWV results. As shown in the Figure, five radiosonde observatories are located in the GPS observatories within 60 km, but, in Sokcho, GPS

Table 1. The information about GPS and radiosonde observatories.

GPS station				RS site			
Name	Latitude (◦)	Longitude (◦)	Altitude (m)	Name	WMO Station number	Altitude (m)	Distance to GPS (km)
BHAO	36.1	128.9	1103	Pohang	47138	4	40
DAEJ	36.3	127.3	91				
JEJU	33.2	126.4	403	Gosan	47185	73	28
KOHG	34.4	127.5	26				
MKPO	34.8	126.3	38	Gwangju	47158	13	51
MLYN	35.4	128.7	10				
SBAO	36.9	128.4	1341				
SKCH	38.2	128.5	18	Sokcho	47090	19	0
SKMA	37.4	126.9	27	Osan	47122	52	45

RS: radiosonde, WMO: World Meteorological Organization.

and radiosonde are observed in the same observatory, as mentioned before. The information about GPS and radiosonde observatories are shown in Table 1.

Sokcho meteorological station is the only upper atmospheric observation station in Gangwon-do and it has been observed air pressure, air temperature, wind direction and wind speed at each altitude by flying radiosonde two times a day since June 1, 2001. The observation site is located on the top of a hill protruded toward the East Sea and the observation conditions are almost not affected by the nearby buildings (http://web.kma.go.kr/aboutkma/intro/gangwon/gangwon_affiliated_03.jsp).

The radiosonde observation is carried out two times a day (4 times a day depending on the situation) at 0000 UTC and 1200 UTC in Sokcho meteorological station and the GPS observatory operated by KASI is located inside the station. In Sokcho meteorological station, the 1524 Model of Jinyang Engineering was used to the year 2000 and then the RS80-15L Model of Vaisala (Finland) was used. From 0000 UTC of May 1, 2007, the DFM-06 Model (Germany) was substituted and, since 0000 UTC of June 1, 2009, the RS92 Model of Vaisala has been used until now.

2.2 Characteristics of the data and the method of the study

Although it may vary depending on the characteristics of ballon filled with hydrogen or helium gas, radiosonde is usually flied in 5 to 8 m/s of elevation speed. It takes about 40 minutes to reach 16 km of altitude in this elevation speed and about 90 minute to reach 30 km of altitude (World Meterorological Organization 2008). Thus, after 30 minutes following the flying, the radiosonde reaches about 12 km of altitude where most of the water vapor in the atmosphere is contained (McMillin et al. 2007).

The accuracy of the radiosonde observation is usually lower than that of the ground surface meteorological observation. The reasons are:

- The measurement is performed as the radiosonde moves in the atmosphere.
- The observation range is wide and the time lapse is long.
- The observation can be easily affected by surrounding circumstances including water droplets, solar radiation and temperature change.
- The reproducibility of individual radiosonde is limited to be verified since radiosonde is to be 'disposed after use.'
- There is no upper atmospheric observation method that is independent upon and more precise than the radiosonde observation and it is difficult to reasonably verify the method for the correction of theoretical and experimental error (So et al. 2007).

In a statistical point of view, the bias and error of radiosonde are classified into systematic bias and random error that are quantitatively expressed as mean bias and root mean square error (RMSE) Systematic bias represents the degree of bias that the sensor has and it can be corrected. Random error represents irregularly varying range of values within the uncertainty of the sensor and smaller random error means higher sensor accuracy (Kim et al. 2009). A reference data to compare the radiosonde data is required in order to derive the systematic bias and random error of a radiosonde. In this study, we used the GPS PWV data measured in 30-minute interval by KASI.

The analysis in this study was focused on the events where the precipitation more than 0.5 mm per hour continued over 30 minutes in Sokcho in the summer seasons

Table 2. GPS and radiosonde PWV in the event of 1-hour rainfall (>0.5 mm) maintained more than 30 minutes during 2007, 2008 summertime.

Launch time and date	PWV (mm)	
	GPS	radiosonde
1200 UTC Jun. 21, 2007	48.3	50.1
0000 UTC Jul. 10, 2007	45.2	45.4
1200 UTC Jul. 10, 2007	42.6	45.7
0000 UTC Jul. 11, 2007	41.4	42.8
1200 UTC Jul. 11, 2007	41.5	43.7
0000 UTC Jul. 13, 2007	36.3	41.8
1200 UTC Aug. 3, 2007	57.6	66.7
1200 UTC Aug. 9, 2007	57.1	66.2
1200 UTC Aug. 26, 2007	52.8	56.5
0000 UTC Aug. 27, 2007	55.6	58.3
1200 UTC Aug. 27, 2007	58.6	63.5
1200 UTC Jun. 4, 2008	28.7	31.8
0000 UTC Jun. 5, 2008	28.1	29.4
1200 UTC Jun. 14, 2008	30.0	31.9
1200 UTC Jun. 21, 2008	48.6	51.6
0000 UTC Jun. 22, 2008	39.9	45.1
1200 UTC Jul. 19, 2008	55.5	62.6
0000 UTC Jul. 20, 2008	59.8	65.6
1200 UTC Jul. 20, 2008	63.9	71.9
0000 UTC Jul. 24, 2008	61.9	54.5
0000 UTC Jul. 25, 2008	61.7	60.7
0000 UTC Jul. 26, 2008	52.6	54.0
0000 UTC Aug. 15, 2008	58.1	63.5
0000 UTC Aug. 18, 2008	63.7	60.0
0000 UTC Aug. 20, 2008	37.1	38.3
0000 UTC Aug. 22, 2008	47.1	48.0
1200 UTC Aug. 22, 2008	55.4	45.3
0000 UTC Aug. 23, 2008	39.1	51.0

(June to August) of 2007 and 2008 when the DFM-06 Model was used. The GPS PWV data that were observed at the radiosonde observation time were compared with the radiosonde PWV. The 60-minute precipitation accumulation data derived by Automatic Weather System (AWS) was used to choose the rainfall events. The AWS rainfall sensor employs a 0.5 mm tipping-bucket rain gauge. Since a 'weak rainfall' usually refers to the rainfall less than 0.2 mm per hour, we chose the events where the raining continued for more than 30 minutes when the radiosonde observation was carried out.

Table 2 shows the GPS and radiosonde PWV data of the selected events. The number of data of the rainfall events is relatively small when compared with that of the non-rainfall events because the GPS observation and radiosonde observation were performed simultaneously only in two times a day since the radiosonde observation was carried out two times per day, while the GPS PWV data were produced in 30-minute interval. In addition, when choosing the rainfall events over 0.5 mm per hour that continued for more than 30 minutes, the events where the rainfall was stopped even for one minute during the 30 minutes of the period were not included in the analysis.

Table 3. Weather conditions for Table 2.

Launch time and date	PWV (mm)			
	CC	CH	Vi	RH
1200 UTC Jun. 21, 2007	10	7	30	91
0000 UTC Jul. 10, 2007	10	7	50	89
1200 UTC Jul. 10, 2007	10	7	40	91
0000 UTC Jul. 11, 2007	10	7	40	92
1200 UTC Jul. 11, 2007	10	7	30	89
0000 UTC Jul. 13, 2007	10	7	20	94
1200 UTC Aug. 3, 2007	10	7	70	90
1200 UTC Aug. 9, 2007	10	7	80	93
1200 UTC Aug. 26, 2007	10	7	100	89
0000 UTC Aug. 27, 2007	10	0	80	86
1200 UTC Aug. 27, 2007	10	7	70	91
1200 UTC Jun. 4, 2008	10	8	100	95
0000 UTC Jun. 5, 2008	10	7	70	96
1200 UTC Jun. 14, 2008	10	7	70	94
1200 UTC Jun. 21, 2008	10	7	40	96
0000 UTC Jun. 22, 2008	10	7	30	97
1200 UTC Jul. 19, 2008	10	8	30	94
0000 UTC Jul. 20, 2008	10	7	20	95
1200 UTC Jul. 20, 2008	10	8	10	96
0000 UTC Jul. 24, 2008	10	7	50	95
0000 UTC Jul. 25, 2008	10	7	30	96
0000 UTC Jul. 26, 2008	10	7	50	96
0000 UTC Aug. 15, 2008	10	8	60	93
0000 UTC Aug. 18, 2008	10	7	70	92
0000 UTC Aug. 20, 2008	10	7	70	93
0000 UTC Aug. 22, 2008	10	7	50	92
1200 UTC Aug. 22, 2008	10	7	30	97
0000 UTC Aug. 23, 2008	10	8	80	96

CC: cloud cover (1/10), CH: Height of Cloud Base (100 m),
Vi: Visibility (100 m), RH: Relative Humidity (%)

Table 3 shows the meteorological conditions of the events shown in Table 2 including cloud cover, height of cloud base, visibility and relative humidity. In all the events, the sky was overcast and the relative humidity was mostly over 90%.

3. RESULTS

The groups of the GPS and radiosonde PWV pairs at the time shown in Table 2 were labeled as WET for the wet period or DRY for the dry period. Based on this, the difference between the GPS PWV and radiosonde PWV was analyzed for the summer seasons of 2007 and 2008 considering rainfall or non-rainfall events.

Figs. 2 and 3 show the GPS and radiosonde PWV time series in Sokcho and their difference. The horizontal axis indicates the time between June 1 to August 31, while the vertical axis indicates PWV in millimeter unit. The time series shows that the data from the two different observations are in a good agreement. However, as found in the PWV difference data in the Figs. 2 and 3, there was a relatively large bias. According to Lee et al. (2008), this result is at a similar level with that of the conventional study (Van Baelen et al. 2005).

To examine the PWV difference depending on the observation instruments, the GPS-derived PWV was comparatively analyzed with the radiosonde PWV and the results are shown in Figs. 4 to 6. In each Figure, the upper part shows the correlation between the observation instruments, while the lower part shows the trend of the (Radiosonde PWV) / (GPS PWV) ratio depending on the GPS PWV change.

As verified in Figs. 2 and 3 the GPS PWV and radiosonde PWV are highly correlated with each other in general. In addition, it was found that the overestimation of the radiosonde PWV relative to the GPS PWV turned into the underestimation as the GPS PWV was increased, except the rainfall events in 2007. This result is similar to the analytical result of Kim et al. (2009) which showed that the wet bias of the radiosonde PWV increased as the GPS PWV decreased and the dry bias of the radiosonde PWV increased as the GPS PWV increased.

In order to analyze the bias and error characteristics of the radiosonde PWV, the mean bias with the GPS PWV and the RMSE were calculated and the results are shown in Table 4. Compared to that of 2007, the mean bias of 2008 was decreased by about 30 % in the dry events and about 50 % in the wet events. However, the RMSE was larger in 2008 than that of 2007 regardless of the rainfall, which indicates that the systematic bias was decreased while the random error increased. In particular, the rate of RMSE increased was larger in the dry events than in the wet events, which may be caused by the anomalous value that is inherent in the radiosonde observation data, as shown in Fig. 5 (Takiguchi et al. 2000).

In the previous study of Kwon et al. (2007) that used the radiosonde data of two years, it was shown that there is dry bias in the radiosonde PWV in comparison with the GPS PWV and the mean bias between the GPS observation and the 12-hour interval radiosonde observation was about 1.5 mm. However, although the mean bias in this study was similar to that of the previous study, the wet bias was larger than the dry bias and even more in the RMSE data. This may be because the result in this study was derived from the data produced in summer when the PWV was highly variable, while Kwon et al. (2007) analyzed the radiosonde observation data over two years. Moreover, spatial error could be included in the analysis of Kwon et al. (2007) because the GPS data from the observatories located in Tamna University (Jeju) and Suwon were also used for the analysis of radiosonde data from Gosan-ri (Jeju) and Osan. On the contrary, spatial error could be excluded in this study since the radiosonde observation and GPS observation were simultaneously carried out in Sokcho observatory. Further, GIPSY-OASIS II (Zumberge et al. 1997) was used in the former study for the GPS data processing, while Bernese 5.0 was used in the latter study. A long-term comparative study with more data is required to derive more objective result.

Table 4. Mean biases and RMSEs of GPS, radiosonde PWV.

	Year	DRY+WET	DRY	WET
mean bias (mm)	2007	-2.8804	-2.7901	-4.0209
	2008	-2.0485	-2.0488	-2.0452
	2007+2008	-2.4301	-2.3934	-2.8214
RMSE (mm)	2007	3.8819	3.7891	4.9051
	2008	5.4627	5.4396	5.6758
	2007+2008	4.8026	4.7443	5.3862

4. SUMMARY AND CONCLUSIONS

In this study, we compared the PWV data derived by the radiosonde observation at Sokcho meteorological station during the summer seasons of 2007 and 2008 with the PWV data from Sokcho GPS observatory provided by KASI. Since, radiosonde observation and GPS observation are carried out simultaneously in Sokcho observatory among the constant GPS observatories operated by KASI, the data could be directly compared excluding the spatial error that takes place when the observations are performed in different positions. Based on this analysis, the characteristics of the radiosonde PWV were investigated considering rainfall events.

The PWV time series of the two observations were in a good agreement with each other in general. The correlation was also high between the GPS PWV and radiosonde PWV. In addition, except the rainfall events in 2007, the overestimation of the radiosonde PWV relative to the GPS PWV turned into the underestimation as the GPS PWV was increased. This result is similar to the result of the previous study which showed that the wet bias of the ra-

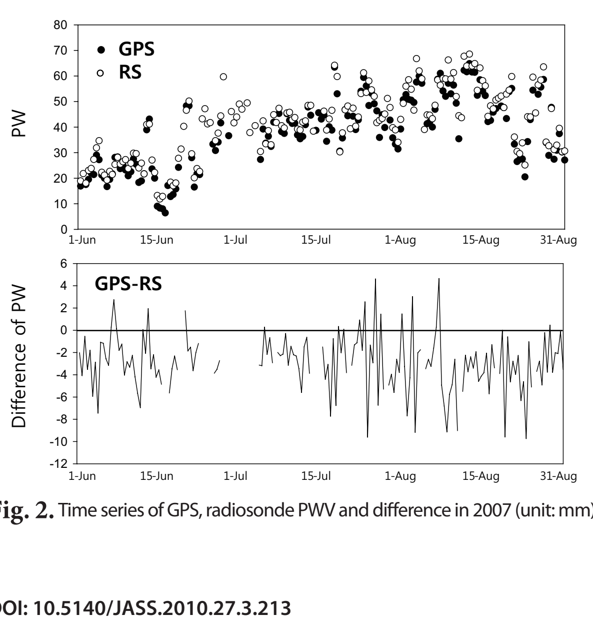

Fig. 2. Time series of GPS, radiosonde PWV and difference in 2007 (unit: mm).

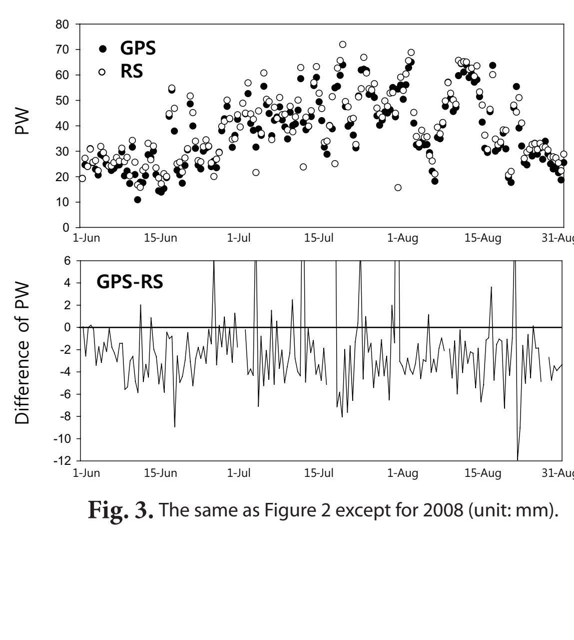

Fig. 3. The same as Figure 2 except for 2008 (unit: mm).

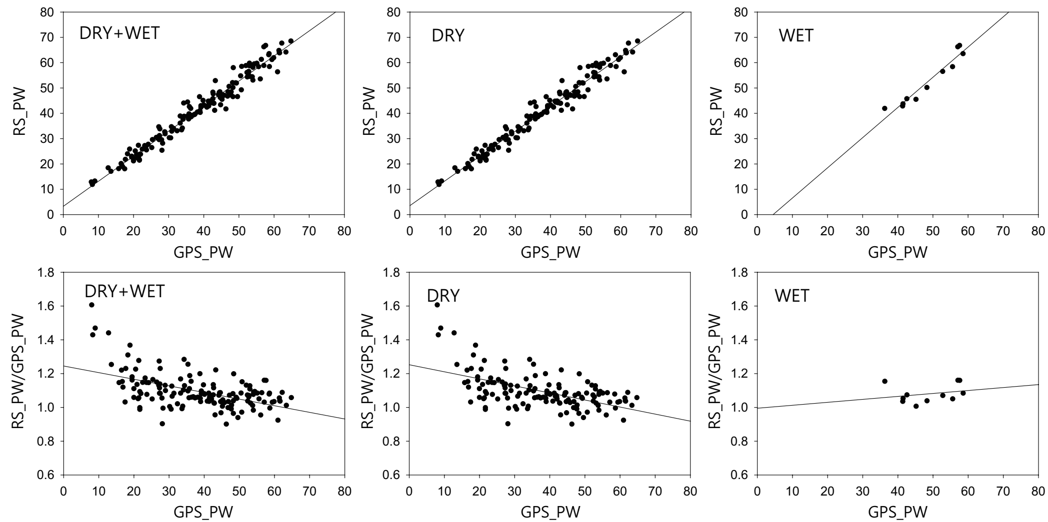

Fig. 4. Scatterplot of GPS, radiosonde PWV (upper) and tendency of (radiosonde PWV) / (GPS PWV) ratio according to GPS PWV in 2007 (unit: mm).

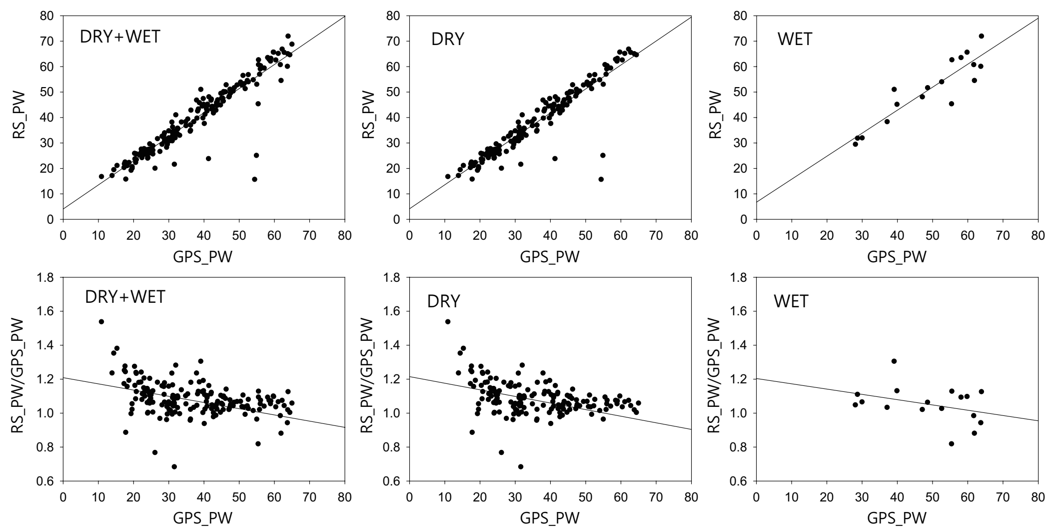

Fig. 5. The same as Figure 4 except for 2008 (unit: mm).

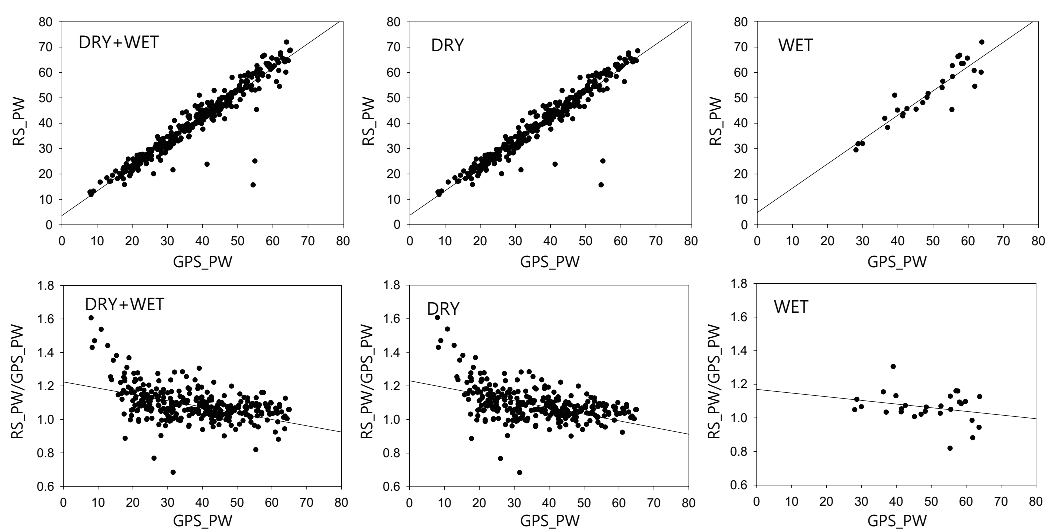

Fig. 6. The same as Figure 4 except for 2007, 2008 (unit: mm).

diosonde PWV increased as the GPS PWV decreased and the dry bias of the radiosonde PWV increased as the GPS PWV increased.

In order to analyze the bias and error characteristics of the radiosonde PWV, the mean bias with the GPS PWV and the RMSE were calculated. Compared to that of 2007, the mean bias of 2008 was decreased by about 30 % in the dry events and about 50% in the wet events, but the RMSE was larger in 2008 than that of 2007 regardless of the rainfall, which indicates that the systematic bias was decreased, while the random error increased. Moreover, different from the previous study, the wet bias of the radiosonde PWV to the GPS PWV was larger than the dry bias and even more in the RMSE data.

The radiosonde bias analysis can provide guidance for the use of radiosonde observation data. However, since the observation data analyzed in this study were not observed at the same time, a study through comparative observation including uniform regulation of the radiosonde flying times is required for the more accurate analysis in comparing observation instruments each other. In addition, it may be necessary to compare long-term data of each season and year for more generalized discussion because the analysis period was short and thus seasonal error factors could be included in this study. It is expected that the comparative analysis of the GPS and radiosonde PWV data in this study can provide the opportunity to reconfirm the usefulness of GPS as a meteorological research tool and contribute to improving the radiosonde humidity sensor accuracy.

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REFERENCES

Bevis, M., Businger, S., Herring, T. A., Rocken, C., Anthes, R., & Ware, R. 1992, JGR, 97, 787

Bevis, M., Chiswell, S., Businger, S., Herring, T. A., & Bock, Y. 1996, Radio Sci., 31, 477

Businger, S. & Coauthors 1996, Bull. Amer. Meteor. Soc., 77, 5

Dach, R., Hugentobler, U., Fridez, P., & Meindl, M. 2007, Bernese GPS Software Version 5.0 (Bern: Printing Office of the University of Bern), pp.1-612

Davis, J. L., Herring, T. A., Shapiro, I. I., Rogers, A. E., & Elgered, G. 1985, Radio Sci., 20, 1593

Duan, J. & Coauthors 1996, J. Appl. Meteor., 35, 830

Durre, I., Williams, C. N., Yin, X., & Vose, R. S. 2009, JGR, 114, D05112

Elgered, G., Davis, J. L., Herring, T. A., & Shapiro, I. I. 1991, JGR, 96, 6541

Elliot, W. P. & Gaffen, D. J. 1991, Bull. Amer. Meteor. Soc., 72, 1507

Kim, K.-H., Kim, Y.-H., & Chang, D.-E. 2009, Atmosphere, 19, 213

Kwon, H.-T., Iwabuchi, T., & Lim, G.-H. 2007, J. Meteor. Soc. Japan, 85, 733

Lee, J., Cho, J., Baek, J., Park, J.-U., & Park, C. 2008, Atmosphere, 18, 417

Lorenc, A. C., Barker, D., Bell, R. S., Macpherson, B., & Maycock, A. J. 1996, Meteor. Atmos. Phys., 60, 3

McMillin, L. M., Zhao, J., Rama Varma Raja, M. K., Gutman, S. I., & Yoe, J. G. 2007, JGR, 112, D13S90, doi:10.1029/2005JD006109

Motell, C., Porter, J., Foster, J., Bevis, M., & Businger, S. 2002, Int. J. Remote Sensing, 23, 2335

Nakamura, H. & Coauthors 2004, J. Meteor. Soc. Japan, 82, 277

Niell, A. E. 1996, JGR, 101, 3227

Rocken, C., Van Hove, T., Johnson, J., Solheim, F., Ware, R., Bevis, M., Chiswell, S., & Businger, S. 1995, J. Atmos. Oceanic Technol., 12, 468

So, S.-S., Suh, M.-S., Lee, C.-W., & So, E.-M. 2007, Upper Atmospheric Observation (Paju-si, Gyeonggi-do: Kyomunsa Ltd. Publisher), p.32

Song, D. S., Yun, H. S., & Cho, J. M. 2002, Korean Journal of Geomatics, 20, 215

Takiguchi, H., Kato, T., Kobayashi, H., & Nakaegawa, T. 2000, EPS, 52, 913

Van Baelen, J., Aubagnac, J. P., & Dabas, A. 2005, J. Atmos. Oceanic Technol., 22, 201

Wang, J., Cole, H. L., Carlson, D. J., Miller, E. R., Beierle, K., Paukknen, A., & Laine, T. K. 2002, J. Atmos. Oceanic Technol., 19, 981

Wang, J. & Zhang, L. 2008, J. Climate, 21, 2218

World Meterorological Organization 2008, Guide to Meteorological Instruments and Methods of Observation, 7th Edition (Genava: WMO Publications), pp.1-673

Zumberge, J. F., Heflin, M. B., Jefferson, D. C., Watkins, M. M., & Webb, F. H. 1997, JGR, 102, 5005