

## Precipitable water vapour monitoring using ground based GPS system

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**सार** – इस शोध पत्र में भारतीय क्षेत्र में ग्लोबल पोजिशनिंग सिस्टम (जी. पी. एस.) का उपयोग करते हुए निकट वास्तविक समय वर्षण जल वाष्प (पी. डब्ल्यू. वी.) संवेदी का विश्लेषण किया गया है। इसमें जी. ए. एम. आई. टी. सॉफ्टवेयर का उपयोग करते हुए निकट वास्तविक समय पी. डब्ल्यू. वी. का निर्धारण करने के लिए प्रत्येक घंटे के अंतर पर पाँच स्टेशनों से एकत्रित किए गए जी. पी. एस. आँकड़ों का उपयोग किया गया है। निकट वास्तविक समय पी. डब्ल्यू. वी. प्राप्त करने के लिए स्लाईडिंग विंडों तकनीक का प्रयोग किया गया। प्रत्येक स्थान के जी. पी. एस. प्रेक्षणों से निर्धारित किए गए पी. डब्ल्यू. वी. की तुलना उनके रेडियोसोँदे मापों के साथ की गई है। इनसे प्राप्त परिणामों से पता चला है कि प्राप्त किए गए जी. पी. एस. वर्षण जल मुक्त रेडियोसोँदे मापों सहित कुछ स्टेशनों के लिए सही पाए गए हैं। हमने घंटेवार वर्षा के प्रेक्षण सहित प्रत्येक घंटे के जी. पी. एस. – पी. डब्ल्यू. वी. की परिवर्तिता की भी जाँच की है और यह पाया है कि पी. डब्ल्यू. वी. में पहले उल्लेखनीय रूप से वृद्धि हुई है और उसके बाद इसमें कमी आई है।

**ABSTRACT.** The sensing of near real time Precipitable Water Vapour (PWV) using Global Positioning System (GPS) over Indian region were analyzed. GPS data collected from five stations at hourly interval were utilized to determine near real time PWV using GAMIT software. Sliding window technique was used to derive near real time PWV. The PWV determined from GPS observations of each site were compared with respective radiosonde measurements. The results shows that the derived GPS precipitable water well agree for some stations with the independent radiosonde measurements. We have also examined the variation of hourly GPS-PWV with hourly rainfall observation and found that PWV increases significantly before the event take place and decreases after the event.

**Key words** – GPS, PWV, RSRW, Zenith total delay, Zenith Hydrostatic delay, Zenith wet delay, Mapping function.

### 1. Introduction

Amount of water vapour in the air is one of the most variable characteristics of the atmosphere. It is an important factor in climate and weather; it regulates air temperature by absorbing thermal radiation both from the Sun and the Earth; it is directly proportional to the latent energy available for the generation of storms; and it is the ultimate source of all forms of condensation and precipitation.

The water vapour in the atmosphere varies both horizontally and vertically with time. The ability of short-term forecast over particular region hindered with the accurate measurement of water vapour timely.

PWV data are potentially valuable for weather and climate modeling and prediction. Kuo *et al.*, (1996) found significant improvement in precipitation forecasts when PWV data are assimilated in numerical weather prediction models. Yuan *et al.*, (1993) simulated the use of PWV data in monitoring global and regional climate change and

found up to 8 mm increase in tropical PWV resulting from doubling of atmospheric CO<sub>2</sub>.

For water vapour measurement, meteorologist traditionally uses radiosonde or water vapour radiometer. Both the method has certain merits and demerits. The ground based water vapour radiometer measure water vapour emission lines (microwave radiation against the cold background) and can estimate the Integrated Water Vapour (IWV) content along the given line of site. The algorithm that is used to retrieve IWV has seasonal and site variation and has to be tuned to the particular site location using independent meteorological measurements. This method has good temporal resolution but poor spatial coverage and their performance degrade in the presence of heavy cloud cover. The space-based Water Vapour (WV) radiometer on the other hand measure water vapour emission lines against the hot background of earth surface and the algorithm used to retrieve WV is greatly complicated over land due to variable hot background of the earth surface and in the presence of cold cloud cover. Both water vapour radiometer techniques are quite

expensive and operational limitations. Both the techniques will fail in severe weather conditions.

The radiosonde, the upper air instrument measure temperature and relative humidity with accuracies of the order 0.2° C and 3.5 % respectively at normal temperature and degrading performance in cold and dry regions Elliot and Gaffen (1991). The highest advantage of this method is the *in-situ* measurements, that provide good vertical resolution, the disadvantage is radiosonde are expendable and the cost of these devices restrict the number of launches to twice daily from limited number of stations and time it consumes to finish a single launch.

Ground based GPS meteorology utilize the GPS receivers co-located with surface meteorological sensors to calculate the total precipitable water directly above the site. A dense network of GPS can be used to estimate the precipitable water at ever half-hour or less with almost of same accuracy level of conventional method. In the present work, the remote sensing of PWV was carried out in high time resolution (hourly) in near real time with the help of Global Positioning System (GPS) installed at various places of India Meteorological Department. The hourly estimated precipitable water in near real time is compared with the RSRW data taken at 0000 UTC and 1200 UTC. Comparison of GPS-PWV with rainfall/thunderstorm activity was also carried out.

### 1.1. Physics of GPS meteorology

The Global Positioning System (GPS) is a satellite-based navigation system made up of a network of 24 to 27 satellites in six orbital planes inclined at 55 degree, four satellites in each orbital plane. The 24 satellites that make up the GPS space segment are orbiting the earth about 12,000 miles above us. They are constantly moving, making two complete orbits in less than 24 hours. These satellites are traveling at speeds of roughly 7,000 miles an hour. GPS works in any weather conditions, anywhere in the world, 24 hours a day.

The GPS satellites carriers atomic clock that transmit time-tagged radio signals at L1 (1.57542 GHz) and L2 (1.22760 GHz). As the GPS signal travels from the satellite to the receiver, it propagates through the ionosphere and neutral troposphere of the earth, where it is retarded and its path changed from a straight line to a curved one. The ionosphere is a weakly ionized plasma layer of the upper atmosphere from about 60 - 1000 km. As a dispersive medium, the ionosphere advances the phase and delays the code of the GPS ranging signals in a frequency-dependent way as they travel through it. These result in errors in the code P1, P2, and carrier phase

measurements L1 and L2 made by the user. The delay due to ionosphere (on the average 10 m) in zenith direction can be determined and removed by observing L1 and L2 frequency using dual frequency receiver. The neutral atmospheric delay consists of Zenith Hydrostatic Delay (ZHD) and Zenith Wet Delay (ZWD). The ZHD can be determined by measuring surface meteorological parameters. ZWD was subsequently derived by subtracting the ZHD form the excess optical length by the neutral atmosphere.

### 1.2. PWV from observed tropospheric delay

Askene and Nordius [1987] shown that integrated precipitable water vapour IPWV can be calculated from the ZWD using a conversion factor Q,

$$Q = \frac{ZWD}{IPWV} = 10^{-8} \left( k_2' + \frac{k_3}{T_m} \right) R_w \rho$$

where,  $k_2'$  and  $k_3$  are constants with the values of  $17 \pm 10 \text{ K hPa}^{-1}$  and  $3.77 \times 10^5 \text{ K}^2 \text{ hPa}^{-1}$ , respectively. Furthermore  $R_w$  is the specific gas constant, which is the ratio of the universal gas constant  $R$  ( $8.314 \text{ J mol}^{-1} \text{ K}^{-1}$ ) and the molar mass of water  $M_w$  ( $18.0152 \text{ g mol}^{-1}$ ), and  $\rho$  is the density of liquid water ( $10^3 \text{ kg m}^{-3}$ ). A weighted mean temperature of the wet atmosphere  $T_m$  is defined as

$$T_m = \frac{\int \left( \frac{e}{T} \right) dz}{\int \left( \frac{e}{T^2} \right) dz}$$

where,  $T$  is the physical temperature in K,  $e$  is the partial pressure of water vapour in hPa and  $z$  is the height. Numerically IPWV in units  $\text{kg/m}^2$  is just the product of  $\rho$  and PWV. Bevis *et al.*, (1992) showed that the ratio PWV/ZWD is approximately various between 0.12 and 0.18 based on location, altitude, season and weather. The best possible accuracy in the estimation of PWV from observed ZWD can be achieved by proper tuning of ' $T_m$ ' for the site. A most powerful approach would be to use operational meteorological models to predict the actual value of ' $T_m$ '. An alternative approach is by using linear surface temperature model. Similar models also reported by Mendes *et al.*, (2000), Solbrig (2000) and Schueler *et al.*, (2001). In the present study, we used linear surface temperature model for  $T_m$  is given by Peng Fang (2007).

$$T_m = 55.8 + 0.77T_s$$

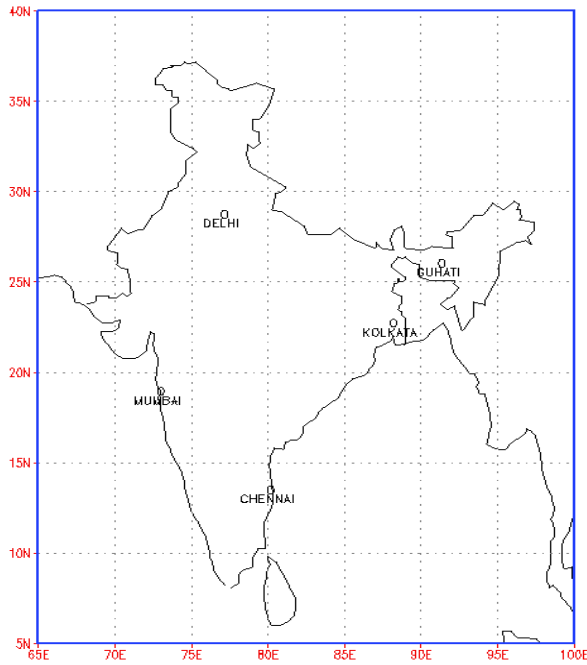


Fig. 1. Map showing location of GPS Sites

1.3. Precipitable water from RSRW

Precipitable water vapour content based on RSRW observation can be estimated using the following formula Curry and Webster (1999).

$$PW = \frac{1}{g} \sum q_i \delta p$$

where ‘g’ (cm/sec<sup>2</sup>) is the acceleration of gravity  $\delta p$  (hPa) is the difference in pressure between layers and  $q_i$  (kg/kg) is the discrete specific humidity measured from sonde observation.

2. Data source and research methodology

We have established five GPS site at New Delhi, Chennai, Mumbai, Kolkata and Guwahati and starts collecting data from the month of April 2007 onwards. The location of GPS sites is shown in Fig. 1. At each site dual frequency Leica GRX1200 receiver were used, which is connected to antenna Leica AX1202 via a 30 m low loss cable. The antenna was fixed at the rooftop of the building (approximately 20 to 30 meters height). A meteorological sensor (Met3A) is also attached near to the antenna pole for temperature, pressure and relative humidity measurement. We fixed the sessions of 30 min in length with 30 seconds sampling interval. Each session

TABLE 1  
Comparison of GPS-PW and RSRW-PW

	Bias	RMSE	R	SD	N
Delhi	2.5369	7.094	0.9495	6.233	1108
Chennai	5.164	8.69	0.8843	6.740	1057
Mumbai	-1.763	7.212	0.9234	6.90	787
Kolkata	1.1757	7.037	0.9482	6.938	445
Guwahati	0.8338	10.222	0.8590	10.00	614

R - Correlation, SD - Standard Deviation, N - No of pairs

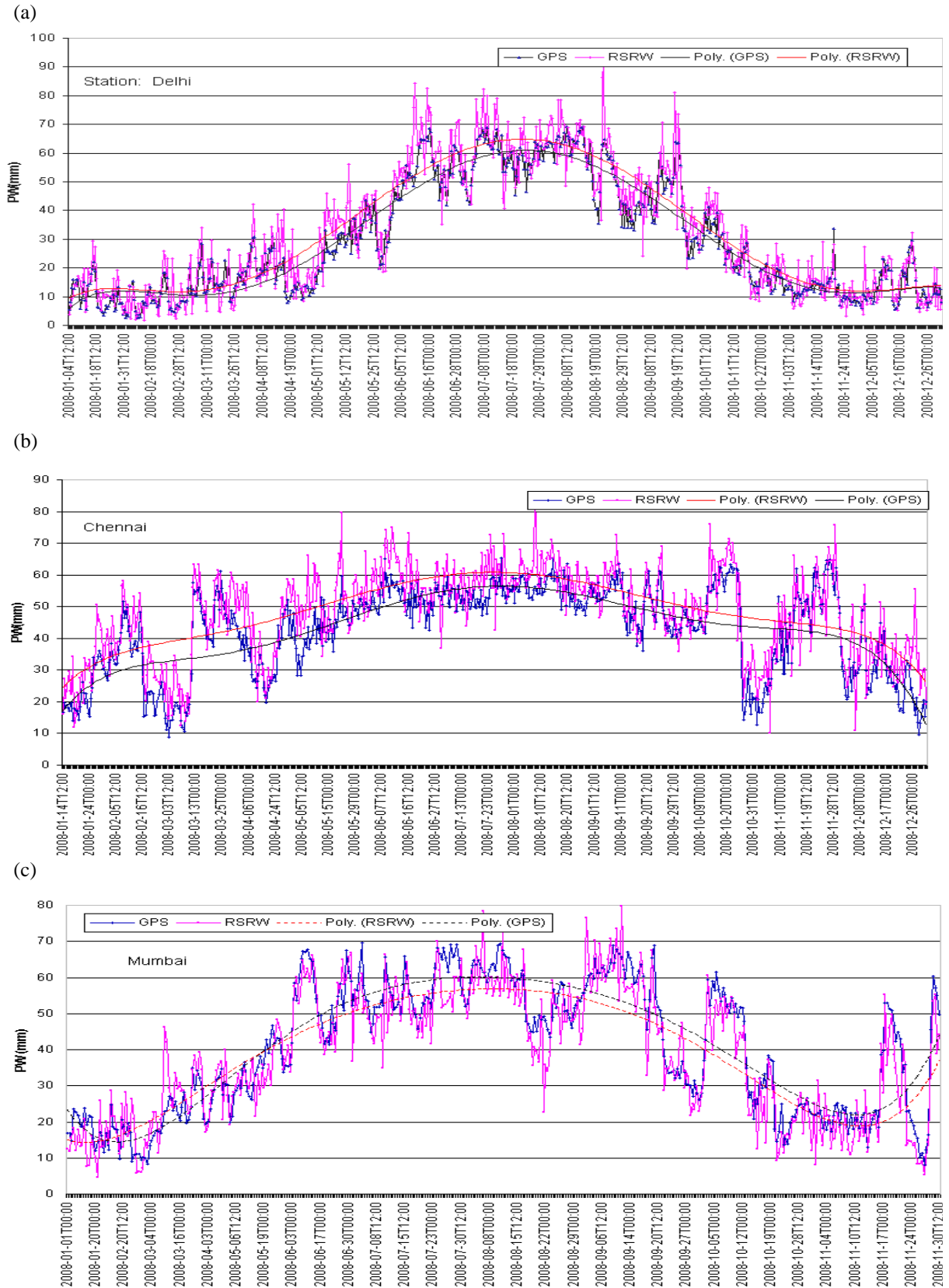
files were downloaded by automatic logging software (spider) run on a PC attached to the receivers.

We employed GAMIT –10.3 King *et al.* (2006) developed by MIT to derive Zenith total delay. Data were collected every 1 hour interval at the central server were processed in near real time using sliding window technique Foster *et al.*, (2005). Niell’s (1996) mapping function was used for signals with arbitrary elevation to determine the total delay and signals less than 10 degree of elevation was rejected to minimize the multi path effect.

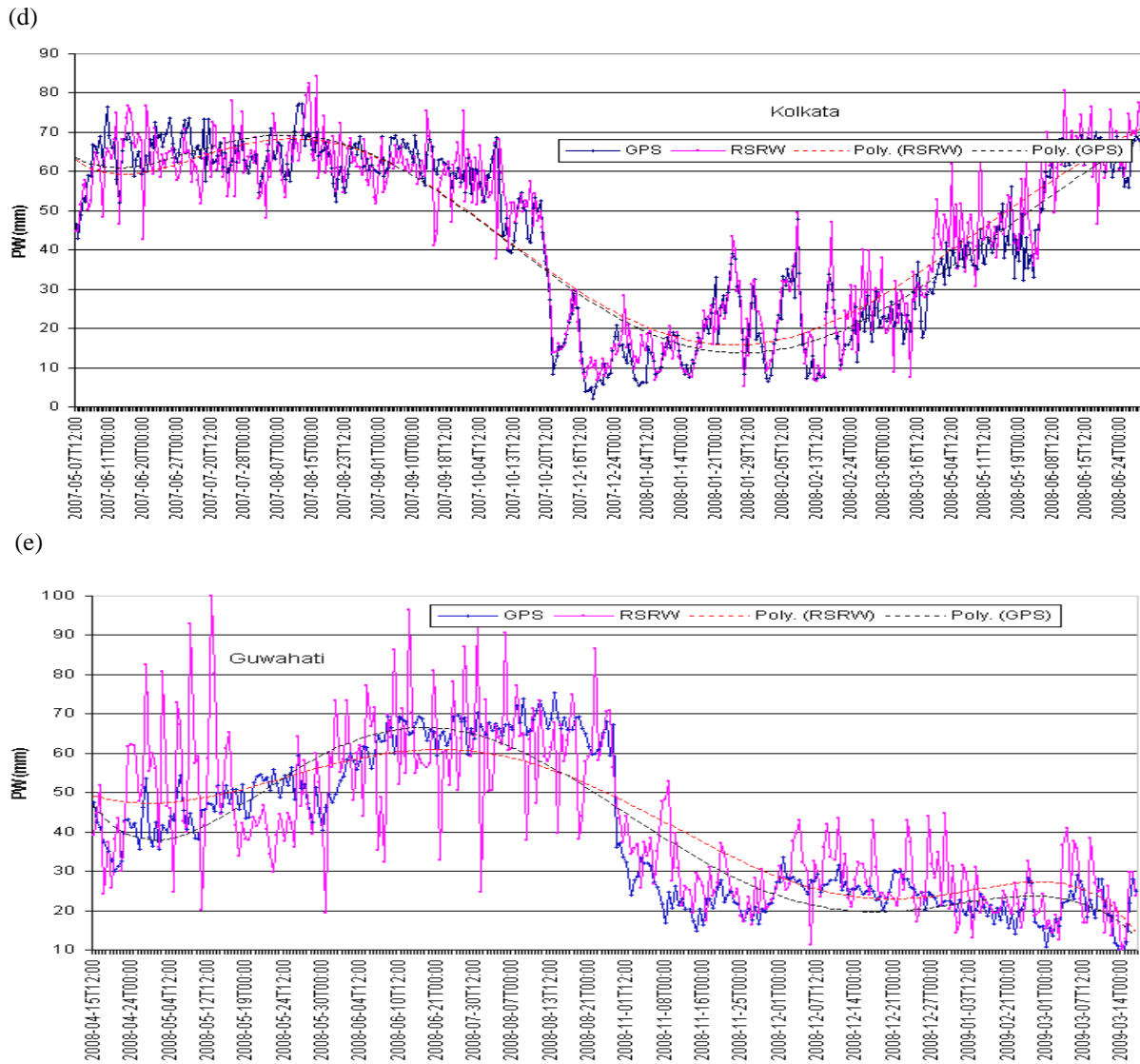
The precipitable water derived from GPS (called GPS-PWV hereafter) at 0000 UTC and 1200 UTC were compared with respective radio sonde precipitable water (here after RSRW-PWV) measurements.

3. Results and discussion

Figs. 2(a-e) shows a comparison between GPS-PWV and RSRW-PWV time series of all the five stations. At the first instant, one can see from the Figs. 2(a-e) that for all five stations the GPS derived PWV has almost same trend with RSRW-PWV. As compared to GPS-PWV, the RSRW-PWV is slightly on higher side except for Mumbai (see the trend lines) and the difference is not constant all the ways. However, if we go point by point then we can find an abnormal fluctuation in RSRW-PWV during pre-monsoon and monsoon period. The fluctuations are more pronounced in Guwahati site followed by Chennai, Kolkata, Mumbai and Delhi sites. Among the five sites, Delhi GPS-PWV is well matching with RSRW-PWV and seems more reliable. Figs. 3(a-e) shows the extent of deviation between RSRW and GPS observations and the result is shown in Table 1. From the Table 1, it is clear that the four sites such as Delhi, Chennai, Guwahati and Kolkata are positively biased and the bias is more for site Chennai (5.164 mm) followed by Delhi (2.5369 mm), Kolkata (1.1757 mm) and Guwahati (0.8338 mm) whereas the site Mumbai is negatively biased (-1.763 mm). This indicates that we need to tune the mean temperature of the



**Figs. 2(a-c).** Time series of GPS-PWV and RSRW-PWV : A comparison (a - Delhi, b - Chennai, c - Mumbai)



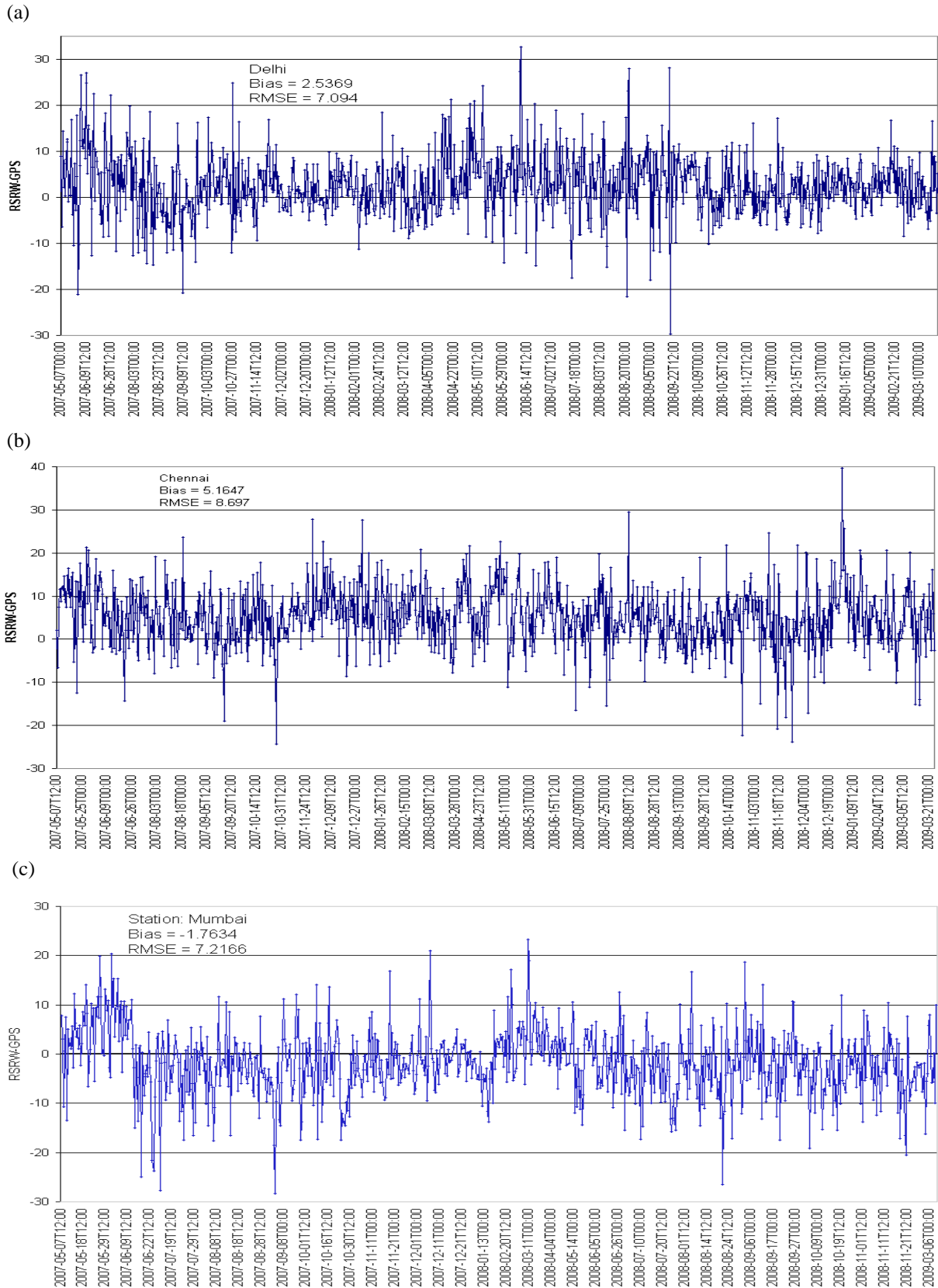
**Figs. 2(d&e).** Time series of GPS-PWV and RSRW-PWV : A comparison (d - Kolkata and e - Guwahati)

atmospheric column independently for each site. The Figs. 2(a-e) also suggest that the mean temperature of the atmospheric is to be tuned according to season and location of the site. If we look into the RMSE, the site Guwahati is having a higher value of 10.22 mm (N = 614) followed by Chennai, Mumbai, Delhi and Kolkata having a value of 8.67, 7.212, 7.094 and 7.037 mm respectively.

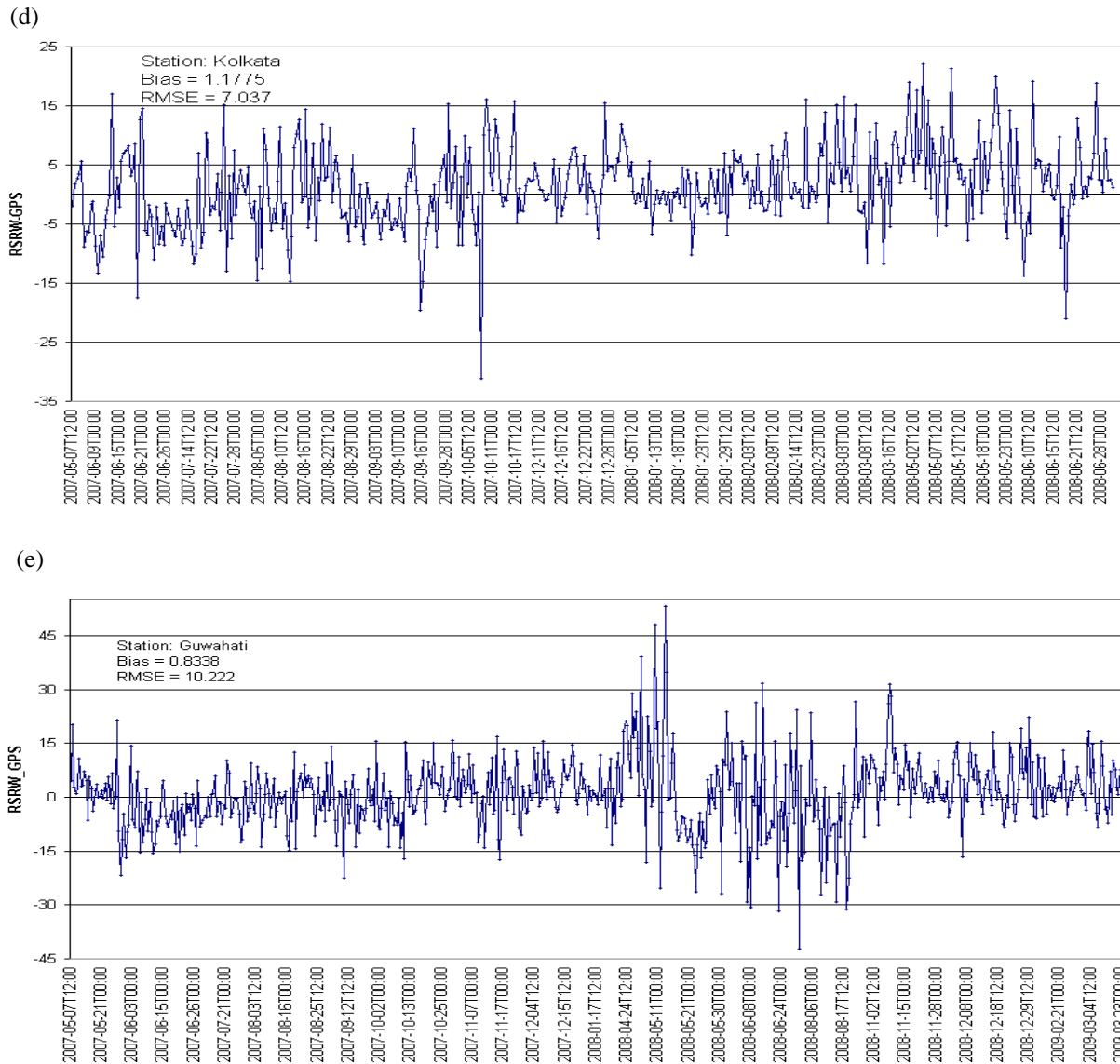
Figs. 4(a-e) shows the relationship between RSRW-PWV and GPS-PWV and the results were shown in Table 1. If both GPS-PWV and RSRW-PWV observations are consistent then the plot shall lie on the line  $y = x$ . However, Figs. 4(a-e) shows the regression

line is deviating significantly from normal. From the Table 1 it is clear that the station Delhi shows the highest correlation coefficient (R) of 0.9495 with less standard deviation (SD) of 6.233 mm followed by Kolkata (R = 0.9482, SD = 6.938 mm), Mumbai (0.9234, 6.9 mm) and Chennai (0.8843, 6.740 mm). On the other hand the site Guwahati showing a less correlation coefficient of R = 0.8590 with higher standard deviation of 10.00 mm.

So far in the above discussions we just compared the two independent observations, *i.e.*, RSRW and GPS of each site. In order to confirm the validity of observation it is necessary to compare these data with the actual



**Figs. 3(a-c).** Bias (a - Delhi, b - Chennai, c - Mumbai)

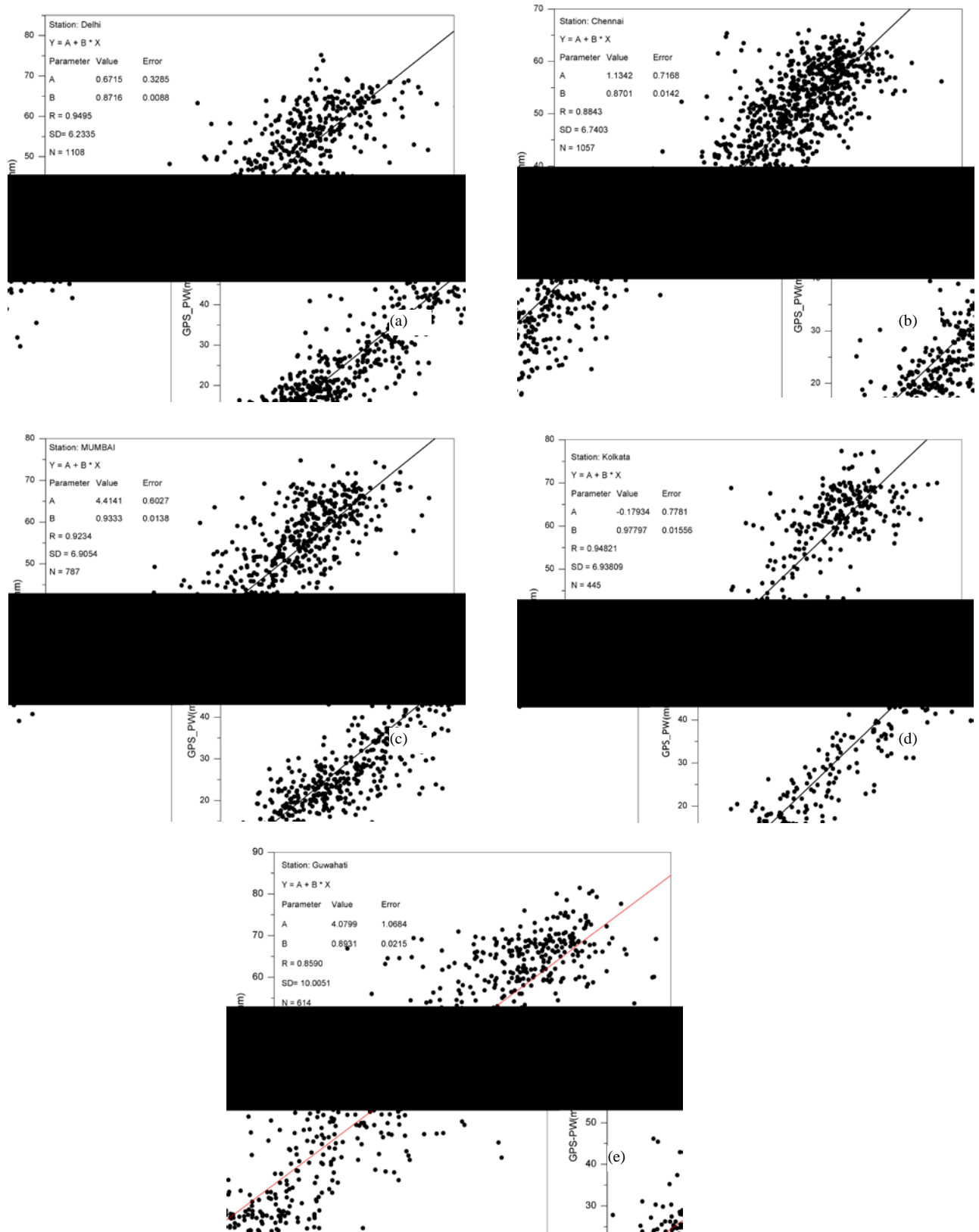


**Figs. 3(d&e).** Bias (d - Kolkata and e - Guwahati)

condition of the weather. Now let us consider the variation of PWV during thunderstorm activity to conclude which observation can give a good result. Figs. 5(a&b) shows the hourly variation of PWV derived from GPS on near real time basis along with observed rainfall (mm). From our past observation during monsoon period whenever GPS-PWV of Delhi reaches more than 61-62 mm, then there is more possibility of rainfall and during pre monsoon this varies from 50 to 55 mm. But this is not true for other stations. For Chennai rainfall starts when PWV becomes 58 - 59 mm and for Kolkata between 62-63 mm and for Mumbai it lies between 59 - 60 mm.

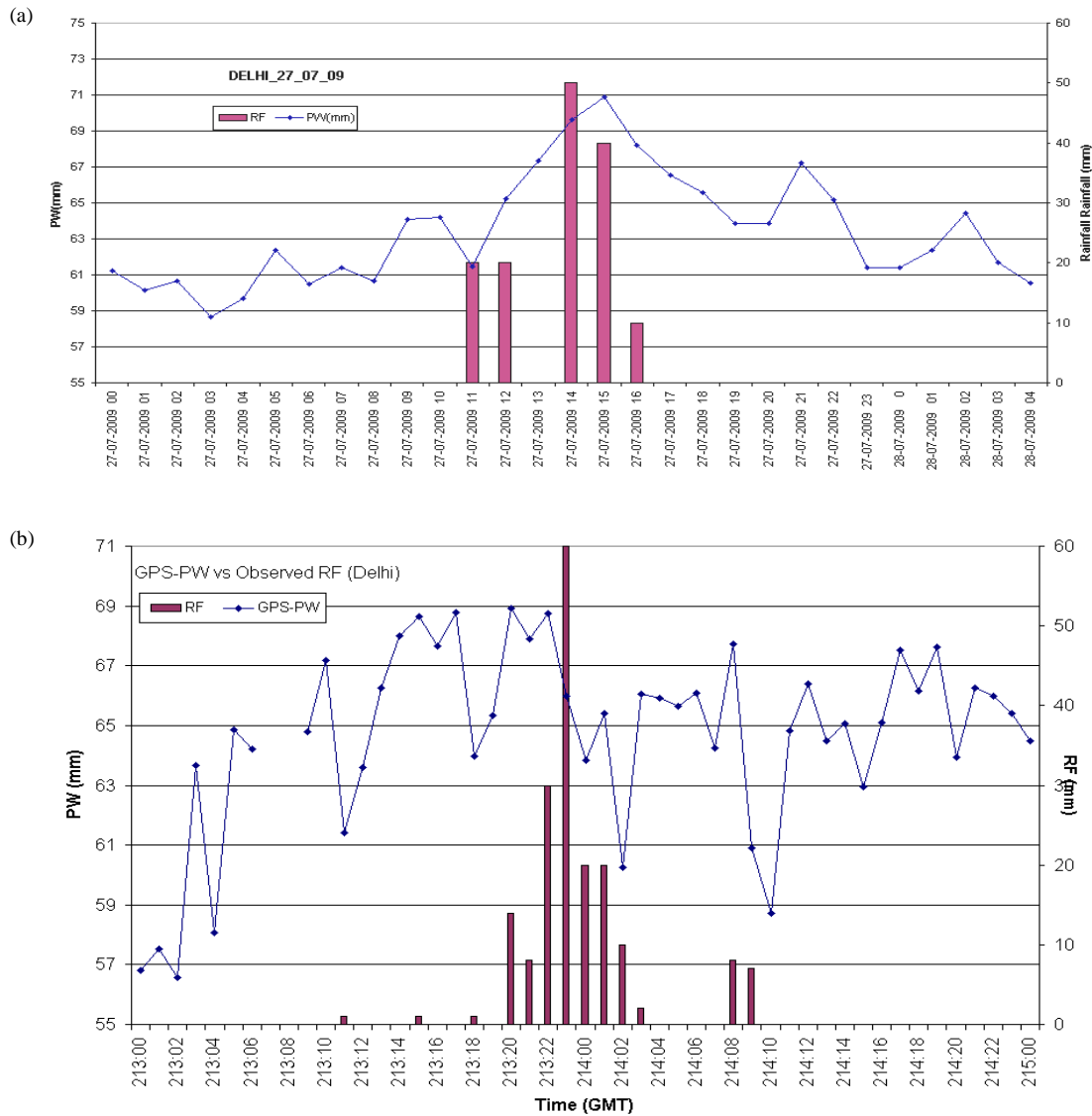
However, in the case of RSRW this is not always true. At several instances, the RSRW observation gives over estimate PWV when there is no event and under estimate PWV when there is an event. The reason may be due to

- (i) First relative humidity of sonde data has offset with surface meteorological data,
- (ii) First temperature of sonde data has offset with surface meteorological data,



**Figs. 4(a-e).** Relationship between RSRW-PWV and GPS-PWV (a - Delhi, b - Chennai, c - Mumbai, d - Kolkata and e - Guwahati)





**Figs. 5(a&b).** Hourly variation of GPS-PWV and observed rainfall over Delhi station, (a) 2009 and (b) 2007

- (iii) Relative humidity shows saturation that may be due to passage in the cloud
- (iv) Termination of observation at the mid altitudes
- (v) Degrading performance of sensors in cold and dry region.
- (vi) Horizontal drifting of RSRW.

Apart from above source of error, the distance between GPS site and RSRW observation may also give some difference. In Chennai, the distance between RSRW

observation (Meenambakkam,) and GPS site (Nungambakkam) is approximately 12 km. Similarly for Kolkata and Mumbai the approximate distance between RSRW and GPS site are 8 km and 20 km respectively. However, we suspect that the difference in PWV estimates between GPS and RSRW are mostly due to sonde data though a part might be come from GPS observation.

#### 4. Conclusion

Comparison between GPS-PWV and RSRW-PWV at all the five stations, shows that there is an appreciable

difference between two types of precipitable water. GPS-PWV on an average less than RSRW-PWV. Among the five sites Delhi GPS-PWV is well coincide with RSRW-PWV and also well agree with observed weather events. On the other hand the site Guwahati shows lot of fluctuation in RSRW observation. One reason for the difference and abrupt change in PWV is considered to be a low vertical resolution of the sounding data especially in the lower atmosphere (up to 500 hPa level) but it needs to be investigated in a future study, as these are complex science questions also. But GPS-PWV in all sites well agree with observed weather events. Although there are errors in GPS-PWV, it shows remarkable changes in PWV before and after rainfall event which confirm its validity.

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