Potential of INSAT-3D Sounder Derived Total Precipitable Water Product for Weather Forecast

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Abstract

The objectives of the INSAT-3D satellite are to enhance the meteorological observations and to monitor the Earth surface for weather forecasting and disaster warning. One of the weather monitoring capability in the INSAT-3D sounder is the estimation of water vapor in the atmosphere. The amount of the water vapor present in the atmospheric column is derived as the total precipitable water (TPW) product from the infrared radiances measured by INSAT-3D sounder. The improvement in the estimation of TPW is carried out by applying the GSICS calibration corrections (Global Space-based Inter-Calibration System) to the radiances from Infra-Red (IR) channels of the sounder, which is done using IMDPS (INSAT Meteorological Data Processing System). The present study is based on TPW derived from INSAT-3D sounder, Radiosonde (RS) observations and corresponding to National Oceanic and Atmospheric Administration (NOAA) satellite. To assess retrieval performances of INSAT-3D sounder derived TPW, RS TPW observations are considered for the validation during May to September 2016 from 34 stations of India Meteorological Department (IMD) is considered for the validation. The analysis is performed on daily, monthly and sub-divisional basis over the Indian region. The comparison of INSAT-3D TPW with RS TPW on daily and monthly basis shows that the root mean square error (RMSE) and correlation coefficients (CC) are~8 mm and 0.8, respectively. However, on sub-divisional and overall scale, the RMSE found to be in the range of 1 to 2 mm and CC was around 0.9 in comparison with RS and NOAA. The spatial distribution of INSAT-3D TPW with actual rainfall observation is also been investigated. In general, INSAT-3D TPW correspond well with rainfall observation however, heavy rainfall events occurs in the presence of high TPW values. In addition, utilizing the TPW from INSAT-3D and ground based Global Navigation Satellite System (GNSS) receiver network, the case studies of thunderstorm events shows good agreement during the

mesoscale activity. The current TPW from INSAT-3D satellite can be utilized operationally for weather monitoring and forecast purpose and it can also offer substantial opportunities for improvement in nowcasting studies.

Keywords: INSAT-3D Sounder, Total Precipitable Water, rain fall.

1. INTRODUCTION

Water vapour is one of the most variable quantities in the troposphere, playing a crucial role in the 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. Latent heat released during cloud formation cloud dominate the structure of diabatic heating of the atmosphere (Trenberth et al., 2005; Trenberth and Stepaniak, 2003a, b). The observations of Total Precipitable Water (TPW) are essential for weather and climate modeling and prediction. The TPW may be used for monitoring the mesoscale to synoptic scale convective activity, monsoonal activities, and moisture gradients. It have shown the significant improvement in precipitation forecasts when TPW is incorporated in the numerical weather prediction models (Kuo et al., 1996). Utilizing the TPW data, (Yuan et al. 1993) showed ~8 mm increment in the tropical TPW resulting from doubling of atmospheric CO_2. The water vapor varies in time and as well as in space (both vertically and horizontally) and the gaps in the observations makes its use impossible for climate and weather forecasting/nowcasting related studies (Trenberth and Olson, 1988). This could be possible with higher temporal and spatial resolution of accurate temperature and moisture profile either from in-situ observations or remotely sensed data. Recently, The Sounder for Atmospheric Profiles of Humidity in the Inter-tropical Regions (SAPHIR) on board Megha-Tropiques satellite has made the RH profiles available in the tropical latitudes (Ratnam et al., 2013). SAPHIR has good spatial coverage with limited temporal resolution.

The products, especially the retrievals of vertical profiles of temperature and humidity, from the sounder of INSAT-3D satellite are important in weather monitoring and forecasting as well as in the study of mesoscale weather phenomena. The higher ground resolution of 10 km and high vertical resolution (about 1 km) along with hourly observations from INSAT-3D sounder provides frequent information on the 3D structure of atmospheric temperature and humidity for the whole Earth disk seen by the satellite (except in and below clouds). They could be used together with the imagers, to produce high resolution cloud detection or water vapor features, to track rapidly evolving phenomena. However, the INSAT-3D sounder observations of TPW are limited for sky conditions (Ratnam et. al., 2016).

In the present study, the TPW derived from INSAT-3D sounder is statistically compared with radiosonde observations and NOAA satellite data over the period May to September 2016. The purpose of this comparison is to investigate the potential of operational hourly TPW product for the monitoring of weather phenomenon over the Indian region. However, initial work using INSAT-3D sounder data was carried out by Mitra et al. 2015, showing the comparison of INSAT-3D data with RS observations from 10 stations of IMD (India Meteorological Department). Utilizing the RS observations from 34 stations and data from ERA-Interim, NCEP re-analysis and other satellites like AIRS, MLS, SAPHIR, Ratnam et al. 2016 showed the reasonable agreement among these datasets. It is shown that there is a large difference between INSAT-3D and other data sets; both in temperature and water vapour above 25 °N latitude; perhaps due to difference in their geometries (Ratnam et al., 2016). In the present paper, we extend the work with 34 RS stations and taking NOAA data on daily, monthly, sub divisional scale followed by case studies with IMD installed network of GNSS TPW. Furthermore, the spatial distribution of INSAT-3D TPW with actual rainfall observation has also been investigated.

2. DATASETS

2.1 INSAT-3D Sounder Scan Processing Strategy

2.1.1 INSAT-3D Sounder Specification

INSAT-3D is advance weather satellite with improved imaging system and atmospheric sounding. The observations of INSAT-3D sounder are utilized to retrieve the vertical profile of the atmosphere in terms of temperature and humidity. INSAT-3D sounder has one visible spectral channel and eighteen channels in shortwave infrared (SWIR), middle infrared (MIR) and long wave infrared (LIR) regions. For all the channels, the ground resolution is 10 × 10 km. The further detail of INSAT-3D sounder can be found elsewhere (Mitra et.al, 2015).

Table 1 Sounder Specification

Channels (Spectral Range Microns)	Resolution
Visible (0.67)	10X10 Km
SWIR (3.67)	10X10 Km
MIR (6.38)	10X10 Km
LWIR (11.66)	10X10 Km

2.1.2 INSAT-3D Sounder Scan Processing Strategy

INSAT-3D scans in the full frame mode which is 18º × 18º North South (NS) covering the entire Earth disc in about 25.7 minutes. Figure 1 shows the areas over Indian land mass (A) and over the southern hemisphere (B) over which the sounder data is being processed by IMDPS (Meteorological Data Processing System), New Delhi on an operational basis. While the Indian land mass is scanned at every hour interval, it is 6 hour interval for the southern hemispheric area. This is the simple scanning strategy kept in such a way that sounding over larger region (land+ocean) will be available every hour. Sounder completes sounding in 10 km × 10 km area in 0.1 second and performs space look operation once every 2 minutes. Black body calibration is performed in every 20 minutes or on command basis. INSAT-3D Sounder have a capability to scan in the steps of 64 × 64 pixels. Scanning of a region covering 640 × 640 pixels that is roughly 6400 km × 6400 km takes ~180 minutes. The benefit of this kind of scan strategy can be utilize for the studies of initial convections, genesis of evolution of squall lines and their fine structures (Purdom et al., 1996a). The INSAT-3D sounder scan strategy can be used for nowcasting and NWP (Numerical Weather Prediction) model assimilation over Indian region.

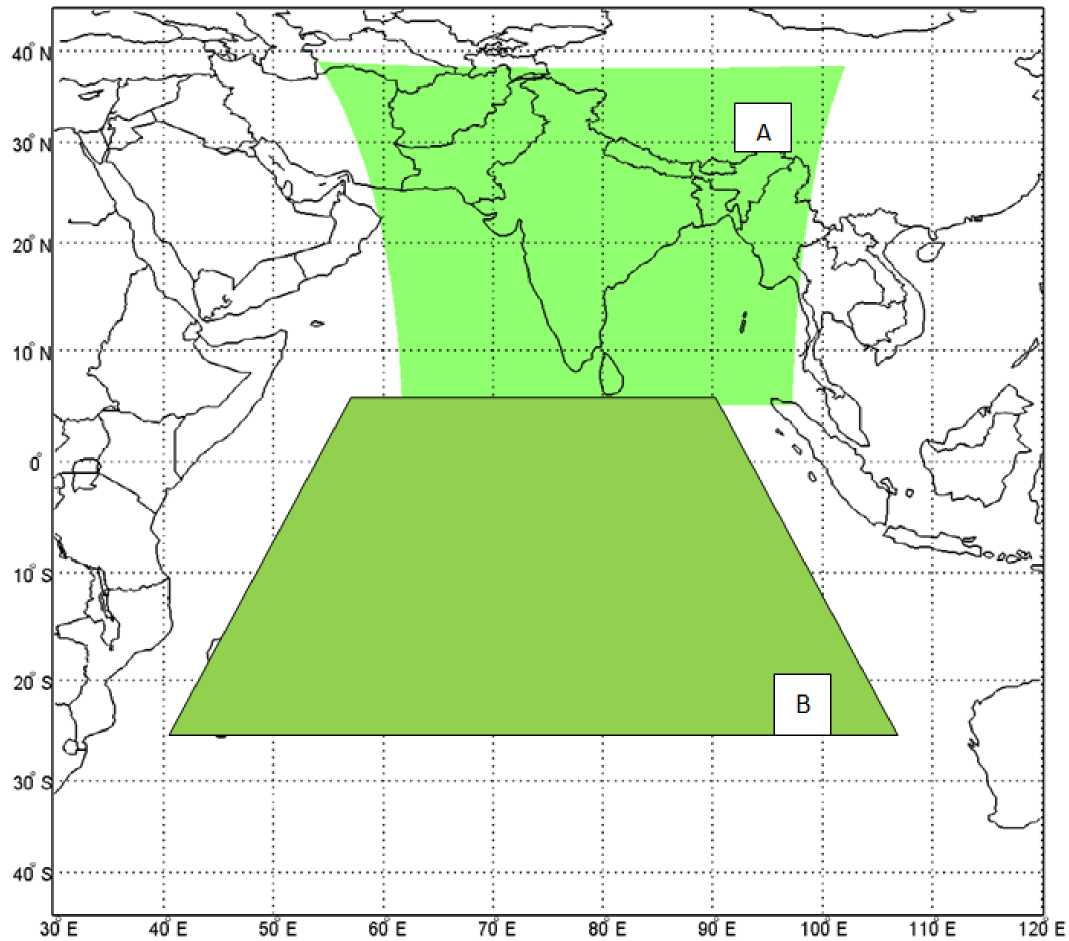


Figure 1. INSAT-3D Sounder scan processing strategy over land and ocean.

2.2 Radiosonde Observations (RS)

In IMD, upper air observations are made at 43 RS stations, 34 RS stations are being used and 62 Pilot Balloon observatories to provide pressure, temperature, humidity & wind at various levels in the atmosphere up to an altitude of 30-35 km. Figure 2 shows the location (marked in red color) of 34 RS stations. Observations from these stations are utilised for the comparison with INSAT-3D TPW. The types of ground equipment used in RS observatories are (1) Radiosonde Ground equipment (ECIL/DIGITAL make) along with X band Win, (2) d finding Radars (EEC/MULTIMET) at 401 MHz and (3) IMS-1500 Radiotheodolite at 1680 MHz and SAMEER Radiotheodolite at 401 MHz. The performance of IMD's GPS radiosonde stations has been very well examined using ECMWF global data (Gajendra Kumar et al., 2011).

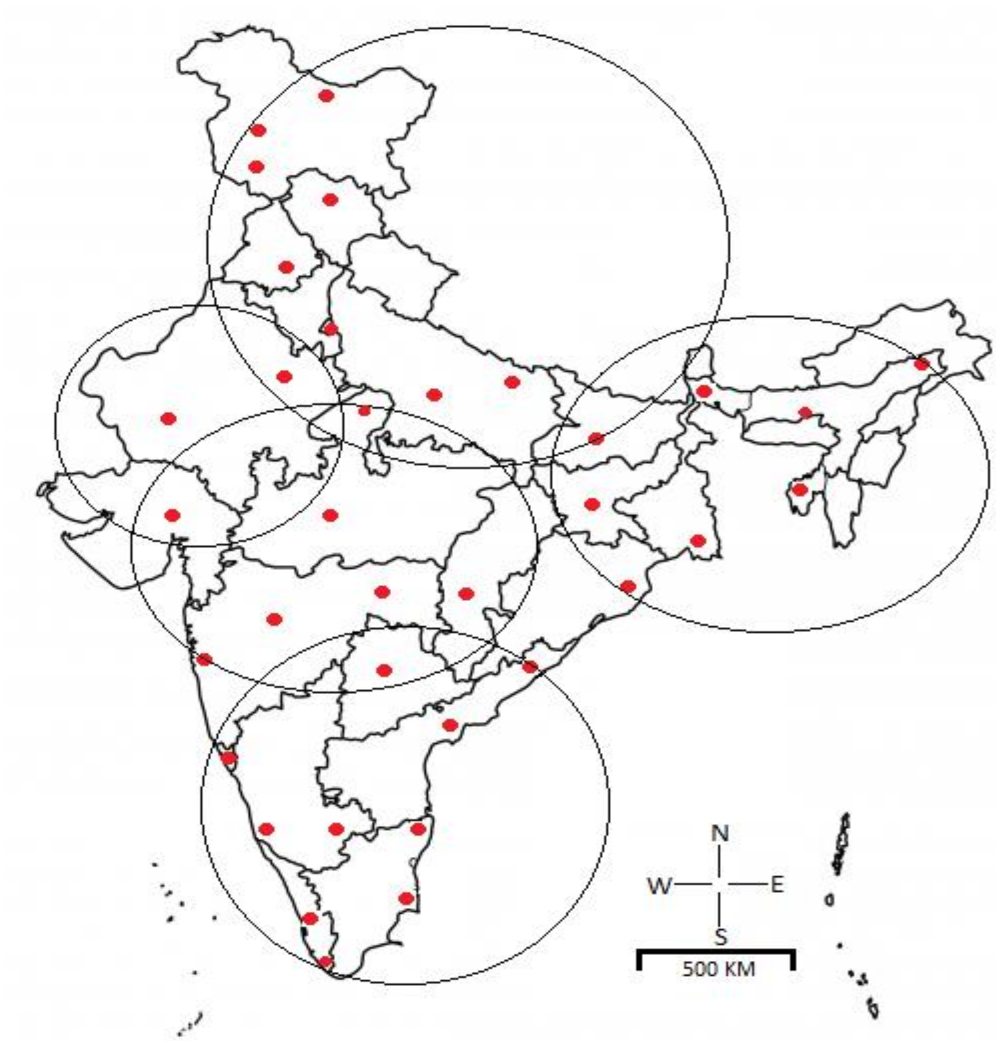


Figure 2. Radiosonde Stations (red dots) of IMD over India. Areas marked with ellipses represent different sub-divisions.

2.3 Global Navigation Satellite System (GNSS)

IMD is augmenting Integrated Network of Global Navigation Satellite System (GNSS) receivers from 5 to 30 for integrated precipitable water vapour (IPWV) measurements. The network is capable of using other GNSS Network data of research institutes in real time basis for enhancing data spatial density and processing. The equipment has advanced meteorological sensors to measure temperature, pressure, humidity of the station and capable of working independently in all-weather condition with high temporal resolution. Though satellites don't often fail, if one fails GNSS receivers can pick up signals from other satellites of the system. The data can be found from http://gnss.imd.gov.in/.

2.4 NOAA's satellite observation

The NOAA (National Oceanic and Atmospheric Administration) Satellite and Information Service provides timely access to global environmental data from satellites and other sources to monitor and understand the atmospheric variation over the Earth in efficient manner. In this study, we used blending TPW from two satellite sources, one from the Advanced Microwave Sounding Unit (AMSU) instruments on NOAA satellites (Ferraro et al., 2005), and the other from the Special Sensor Microwave Imager (SSM/I) instruments on Defence Meteorological Satellite Program (DMSP) satellites. In the blended Total Precipitable Water (TPW) product, individual biases of the data sources have been mitigated to produce a more meteorologically significant product. Blending retrieval procedure has detailed (Kidder et al., 2007) and methodology provides seamless global coverage without gaps to allow for the analysis of atmospheric moisture over land and ocean (Schmit et al., 2002 and Smith et al., 2007). The products are on a Mercator projection with 16 km resolution at the equator. The products are hourly in HDF-EOS file format. These operational products were produced by the NOAA/NESDIS (National Environmental Satellite, Data, and Information Service) Office of Satellite and Product Operations (OSPO).

2.5 GSICS based inter-calibration

There is an on-board blackbody which is responsible for generation of calibration information for all the IR channels in the sounder. In-orbit readings of blackbody temperatures revealed a gradient among the sensor which led to inaccuracy in getting the correct blackbody temperature. It was also observed that during satellite midnight, sun-rays from behind the Earth enter directly into the sensor and hence lead to increase in blackbody temperatures. This phenomenon leads to generation of incorrect calibration information. In order to provide climate quality products and to improve the calibration coefficients, GSICS (Global Space based Inter calibration System) based inter-calibration is used for INSAT-3D. The GSICS aims to inter-calibrate a diverse range of satellite instruments, to produce corrections ensuring consistency in satellite dataset. Allowing usage of calibration data, it produces globally homogeneous products for environmental monitoring. In addition, GSICS develops common methodologies to check the quality of sensors operated by various satellite agencies over the worldwide. The post launch calibration strategy involves spectral response function of sensors, sensor performances and inter-calibration of satellite sensor. And finally, recalibration of archived data or products of sensors is carried out, if necessary. The channel wise GSICS coefficient are found and applied in during the Radiometric Correction process.

3. METHODOLOGY

INSAT-3D retrieval algorithm under IMDPS at New Delhi, is designed for retrieving vertical profiles of atmospheric temperature and moisture from clear sky infrared radiances measured over different absorption bands (http://www.imd.gov.in/INSAT-3D/categouge). The observed radiance in various sounder channels are processed on an hourly time scale. IMD, New Delhi has adapted sounder retrieval scheme from the operational High resolution Infrared Radiation Sounder (HIRS) processing scheme and Geostationary Operational Environmental Satellites (GOES) algorithms developed by Cooperative Institute for Meteorological Satellite Studies (CIMSS), University of Wisconsin, USA (Ma et al., 1999 and Li et al., 2000). In this scheme, physical and regression based retrievals are employed, which includes spectral bands in and around the CO_2 and H_2O absorbing bands. In the scheme, computation of the hybrid first guess atmospheric profiles is using linear combination of regression retrieval and NWP model forecast (Mitra et al., 2015). The methodology has followed by non-linear physical retrieval procedure (Li et al., 2000 and Ma et al., 1999) for the consistency with the sounder observations. The Pressure layer Fast Algorithm for Atmospheric Transmittance (PFAAST) radiative transfer model (Hanon et al., 1996) has been used for forward computation of sounder channel radiances along with Jacobians. As mentioned before, GSICS corrections have been incorporated in the INSAT-3D sounder radiances.

Mathematically, if a(p) is the mixing ratio at the pressure level, p, then the precipitable water vapor W, contained in a layer bounded by pressures p_1 and p_2 is given by

$$\text{INSAT3D Precipitable Water Vapor} = \frac{1}{\rho g}\int_{p1}^{p2} a\,dp$$

Where ρ represents the density of water and g is the gravity constant (9.8 m/s^2). Further details can be found at http://www.imd.gov.in/INSAT-3D/categouge.

The each RS observation was paired with closest INSAT-3D TPW and patterned according to criteria suggested in Fuelberg and Olson (1991).The collocation criteria for INSAT-3D retrievals with RS and NOAA data are based on the following. (1) The absolute distance between the position (latitude and longitude) of the RS and the INSAT-3D retrievals is 0.5º (50 Km) or smaller. This will minimize the differences arising from horizontal gradients in water vapor or TPW. (2) The temporal difference between two sets of data is around ±120 minutes depending on retrievals and location of the RS station. (3) The timing of INSAT-3D and RS observations was matched at 0000 and 1200 UTC.

4. RESULTS AND DISCUSSIONS

4.1 Comparison of INSAT-3D with RS and NOAA TPW at Daily, Monthly and Sub Division Scales

INSAT-3D derived TPW is available at hourly interval over the Indian region. For validation purposes of TPW and its usefulness in weather monitoring and forecast, it is desirable to compare INSAT-3D TPW at different time scales with different sets of data. Thus, on a daily scale, we compared the INSAT-3D TPW with all the collocated measurements of RS TPW. On monthly scale, monthly averaged data on collocated points were used. For sub-division scale, five different regions categorized according to meteorological subdivisions are, Northern India (NI), Eastern India (EI), Central India (CI), Western India (WI) and Peninsular India (PS) (Figure 2).

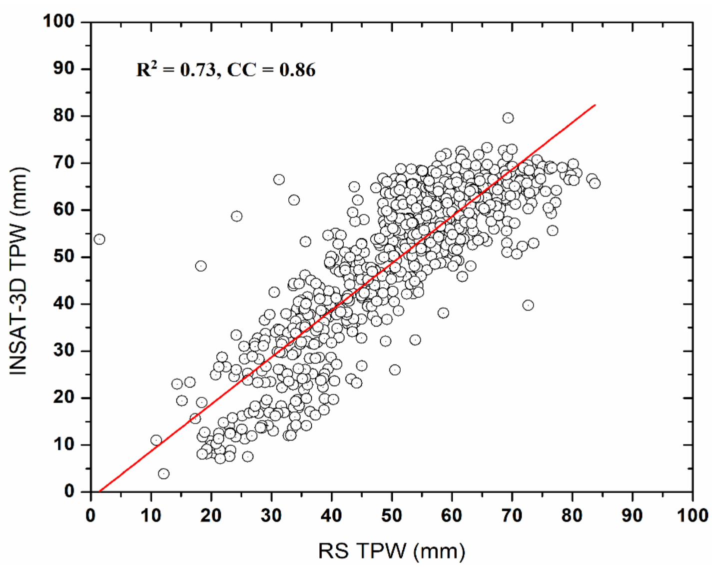
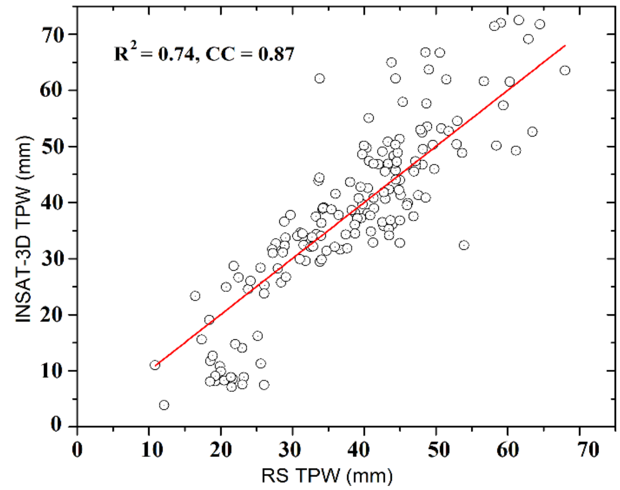


Figure 3. Comparison of INSAT-3D derived TPW with RS observed TPW from May to September 2016

Figure 3 shows the comparison of INSAT-3D TPW and RS TPW on daily scale during May-September 2016. On day to day basis, INSAT-3D TPW agrees well with RS TPW. INSAT-3D TPW is able to measure the synoptic features of weather phenomena at monthly scale over the Indian region very well. However magnitude differs, it can be termed as source of error due to registration and navigation issues during the night time. The consistent and better correlation has seen above 40 mm of TPW values, whereas for less than 40 mm TPW values, INSAT-3D underestimates slightly. This is due attributed to seasonal variation, orographic of the region and different climatic zone over India. The largest differences are observed mainly over mountainous areas and/or near the sea, which reveal differences in representativeness. Good confidence in INSAT-3D TPW estimates is gained during periods of moderate to heavy rain. The overall correlation on daily scale was found to be 0.86. In the previous study, (Mitra et al., 2015) reported 0.73 correlations using 10 IMD stations.

Figure 4 shows the comparison of INSAT-3D TPW and RS TPW on Monthly scale during May-September 2016. The correlation coefficients are in the range of 0.78-0.87. It can be noticed that during monsoon period, specially in the month of June, July and August, when heavy rainfall (above 64.5 mm) occurs, INSAT-3D TPW shows well agreement with RS TPW. Mostly INSAT-3D TPW is higher when rainfall occurrence is higher above 40 mm. The statistics corresponding to this comparison is shown in table 2. INSAT-3D coefficients of variation are high as compared with RS, which indicates the higher variability in total precipitable water. The mean difference between RS and INSAT-3D TPW is much higher in the month of July 5.57 mm. It is due to the substantial rainfall during the monsoon season and in the subsequent months August and September 5.24, 5.3 mm respectively. It was also reported by (Ratnam et al., 2016) that mean difference in the water vapor is as high as 20-30%. The dry basis of 10-25% in INSAT-3D channel compare to similar satellite and reanalysis dataset was also noted. The coefficient of variation is lower for the months July to September, 2016. The coefficient of skewness found negative between INSAT-3D and RS measurement, which indicates mean is less than the mode of the data. The correlation coefficient show good agreement with RMSE for June to September, 2016 except in the month of July. The student’s t-test calculated for significance of computed parameter. The student’s t-test shows the statistical significance of linear relationship among the data, i.e. INSAT-3D TPW and RS TPW.



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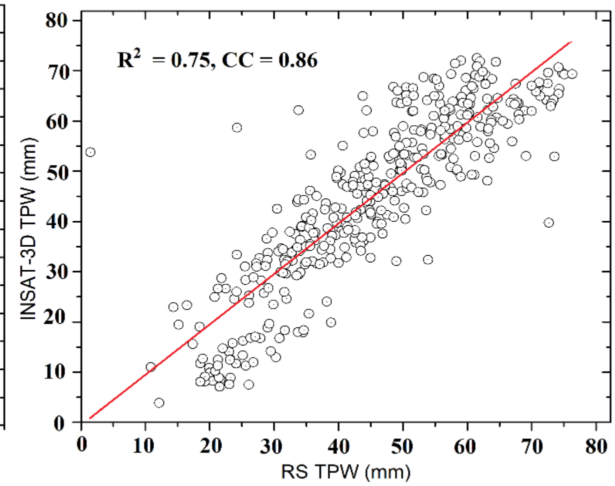

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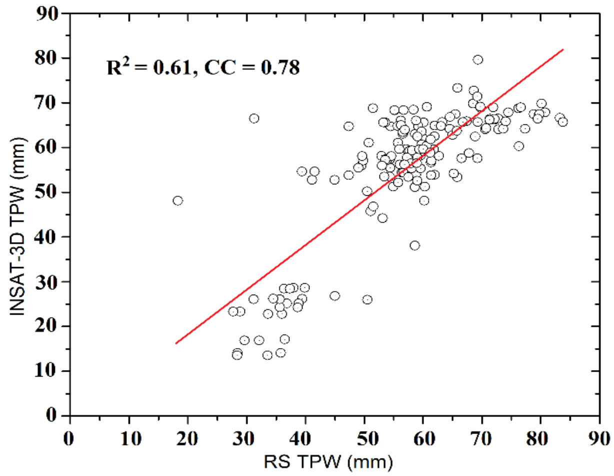

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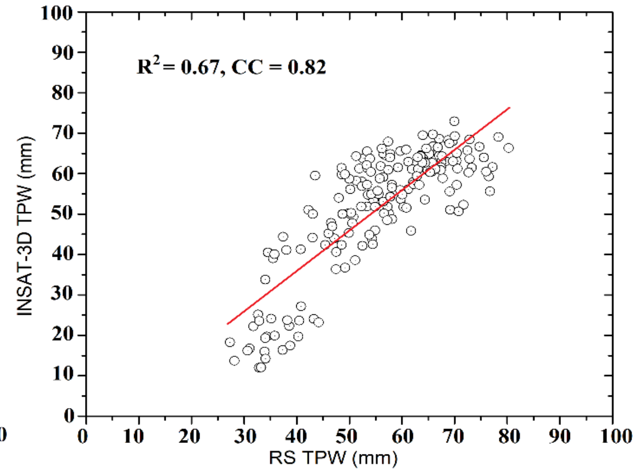

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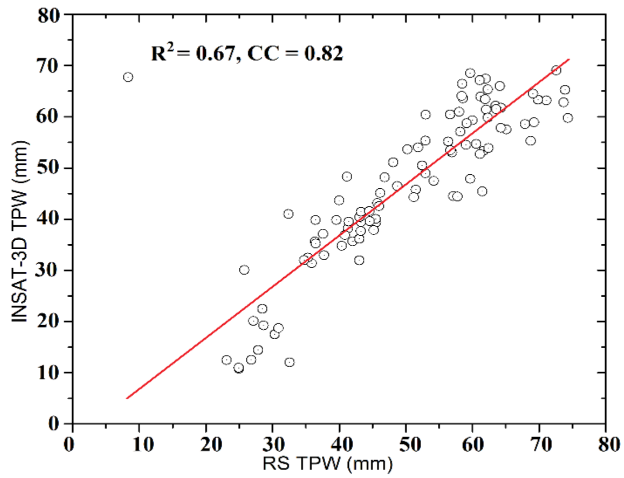

September

Figure 4. INSAT-3D sounder TPW with RS for May, June, July, August and September 2016

Table 2. Statistics and correlation between total precipitable water measured by INSAT-3D and RS

Month	**INSAT-3D**	**RS**	**INSAT-3D**	**RS**	**INSAT-3D**	**RS**	**INSAT-3D**	**RS**	**CC**	**RMSE (mm)**	**t-test**
	Arithmetic Mean (mm)		**Standard Deviation**		**Coefficient of Variation**		**Coefficient of Skewness**				
May	39.36	39.87	15.40	12.51	0.39	0.31	-0.21	-0.10	0.87	7.69	0.359931
Jun	49.75	52.66	16.44	14.16	0.33	0.26	-0.87	-0.57	0.86	8.50	0.049282
July	54.87	60.44	14.59	12.53	0.26	0.20	-1.45	-0.61	0.78	9.31	0.000012
Aug	52.09	57.33	14.71	11.97	0.28	0.20	-1.24	-0.49	0.82	8.73	0.000022
Sep	49.00	54.30	14.14	13.69	0.28	0.25	-1.01	-0.31	0.82	8.79	0.000213

Figure 5 shows the comparison of INSAT-3D TPW with RS TPW and NOAA TPW on sub divisional scale during May to September 2016. It can be clearly seen from the figures that INSAT-3D TPW is underestimating whereas it is over estimating the NOAA TPW for the entire region during the monsoon period. A good correlation is observed for the region, CI and PS as compared to EI and NI regions. However, opposite trend were found while comparing INSAT-3D TPW with NOAA TPW. INSAT-3D TPW is always higher over NOAA data. One of the possible reasons is that INSAT-3D sounder derived TPW were calculated from the radiances sampled every hour while NOAA TPW were based on only two satellite passes with equator crossing times of 0230 and 1430 local time (in Indian Standard Time). Therefore, the sampling frequency of the radiometer is much higher in a geostationary satellite than polar satellite. In general, sub-divisional comparison reveals that the INSAT-3D TPW agrees well RS and NOAA TPW below 23°N whereas the difference is higher above 23°N.

The table 3 shows the statistics for the comparison of TPWs from INSAT-3D, RS and NOAA at the subdivisions in India. INSAT-3D coefficients of variation are similar to that of RS, but in case of NOAA it is higher with respect to INSAT-3D and RS. The coefficient of skewness values found negative for INSAT-3D, RS and NOAA measurement. The correlation coefficients how good agreement between INSAT-3D and NOAA (0.96) as well as between INSAT-3D and RS (0.87) during June to September, 2016.

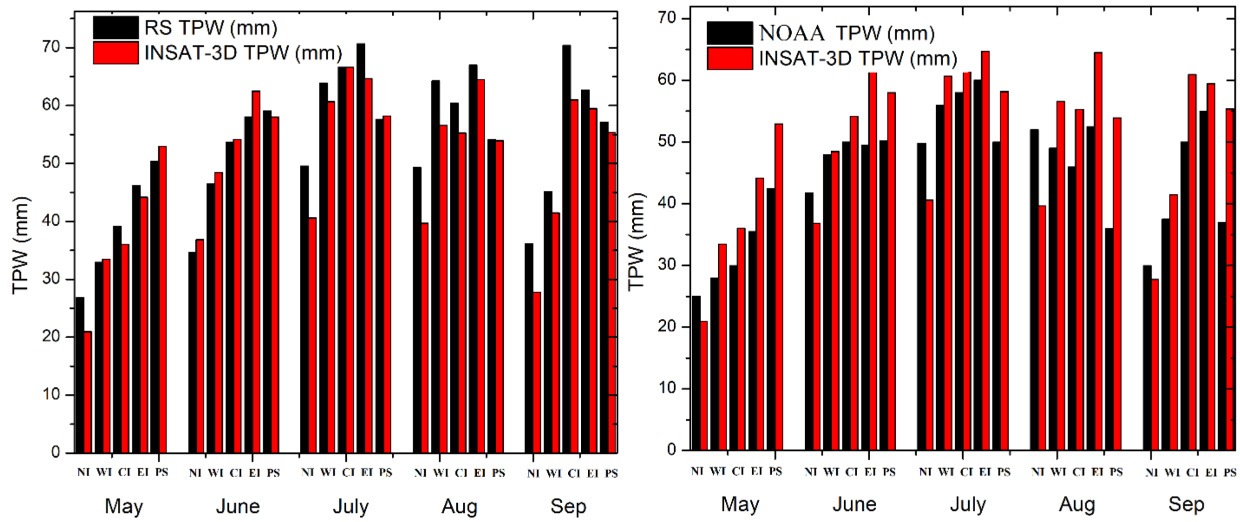

Figure 5. Comparison of INSAT-3D derived with RS and NOAA observed TPW sub-division scales NI, WI, CI, WI & PS from May to September 2016

Table 3. Statistics of INSAT-3D derived, RS and NOAA observed TPW sub-division scales of India

Sub div.	Sensors	Arithmetic Mean	SD	Coefficient of Variation	Coefficient of Skewness	NOAA vs INSAT-3D			INSAT-3D vs RS		
						BIAS	RMSE	CC	BIAS	RMSE	CC
NI	NOAA	39.71	11.91	0.30	-0.29	1.3	1.09	0.97	1.22	1.15	0.87
	INSAT-3D	33.16	8.51	0.25	-0.84						
	RS	39.28	9.91	0.25	0.005						
WI	NOAA	43.7	10.98	0.25	-0.63	-0.88	0.88	0.97	0.47	0.77	0.97
	INSAT-3D	48.13	11.04	0.22	-0.26						
	RS	50.52	13.42	0.26	-0.12						
CI	NOAA	46.8	10.35	0.22	-1.22	-1.56	1.23	0.97	0.79	0.83	0.96
	INSAT-3D	54.61	11.51	0.21	-1.20						
	RS	58.58	12.83	0.21	-0.90						
EI	NOAA	50.5	9.22	0.18	-1.28	-1.71	1.27	0.91	0.37	0.83	0.91
	INSAT-3D	59.05	8.58	0.14	-1.92						

	RS	60.92	9.47	0.15	-1.00						
PS	NOAA	43.14	6.81	0.15	0.10	-2.5	1.55	0.77	-0.002	0.45	0.92
	INSAT-3D	55.68	2.36	0.04	0.05						
	RS	55.66	3.44	0.06	-1.00						

4.2 Comparison of INSAT-3D TPW with Actual Rainfall Observation

The box-whisker plot shown in the Figure 6 compares the actual rainfall observation and INSAT-3D TPW for different values during June to September 2016. This figure is constructed from the daily rainfall observation between 0 to 140 mm occurring over the 34 stations and collocated mean INSAT-3D TPW values between 0 to 90 mm over the entire Indian region. It can be seen from the Figure 6, that TPW is binned for the ranges 0-20, 21-40, 41-60, 61-81 and >80. As seen from the whiskers, the rainfall has least scatter for the 0-20 bin, while for TPW >80 it shows most scatter. The mean and median are almost same for all the TPW bins, except for the TPW >80. There exist exponential behavior between rainfall amounts with higher INSAT-3D TPW values. However, further analysis with more number of observations is required for the quantification of non-linear/exponential relationship. However, atmospheric constituents and synoptic scale of monsoon conditions are an important factor when considering the occurrence of rainfall and satellite derived TPW. It is well demonstrated from the Figure 6, that the heavy and heavy to very heavy rainfall are corresponding to the higher TPW values (60-80 mm and above 80mm). The TPW corresponds to the cloud-free observations and rainfall measurements are for cloudy atmosphere. This can be obviously related to the fact that the heavy rainfall occurs in the presence of higher TPW values (Wu et al., 2003). However, for the light to moderate rainfall amount (less than 40 mm) INSAT-3D TPW is comparable. The moisture convergence, advection of moisture over geographical locations of the subdivisions occasionally receive heavy to very heavy rainfall due to synoptic scale monsoon circulations or its orography. The areas having high orographic region like north eastern parts, Jammu-Kashmir and parts of the Western Ghats (in the west coast of India), have less evaporation and high rainfall as the moisture laden air mass is transported over the regions (Ratnam et al., 2016). Similarly, it is also observed that the rainfall is overestimated in the dry conditions because the falling raindrop evaporates before coming to the surface in dry conditions resulting in the overestimation of rainfall.

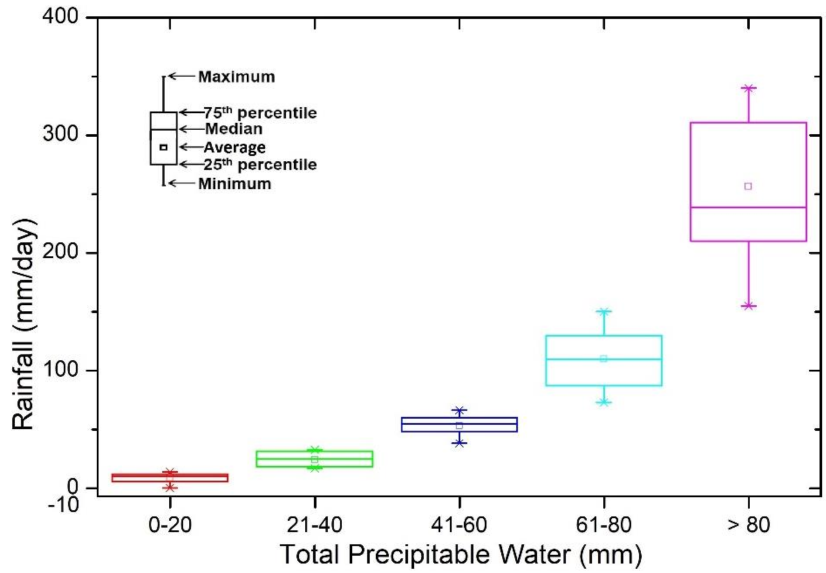

Figure 6. The Box-Whisker plot for comparison of INSAT-3D TPW with actual rainfall over Indian region

4.3 Case studies of INSAT-3D TPW with ground base GNSS TPW

In these case studies, hourly INSAT-3D sounder derived TPW, and GNSS TPW were analyzed for a thunderstorm events occurred in Pune, Kochi and Dibrugarh respectively latitude and longitude 18.52° E 73.85° N on June 3, 2017 at 1200 UTC, 9.93° E 76.26° N on June 6, 2017 at 0600 UTC and 27.47° E 94.91° N on June 9, 2017 at 0000 UTC. The advantage of GNSS is having access to multiple satellites, redundancy and availability at all times. Further details can be found at http://gnss.imd.gov.in/.

Figure 7 shows the hourly comparison between TPW derived from INSAT and GNSS during thunderstorm events. The grey bar shows the time of occurrence (i.e., 1200 UTC) of thunderstorm over Pune city. It was observed from the satellite imageries (not shown here) that initial convection development starts at 0600 UTC with multiple significant convections. It can be seen from the Figure 7 that the INSAT-3D TPW is showing the higher TPW values around 53 mm in comparison with GNSS TPW of 54 mm at 0600 UTC. The higher TPW of INSAT-3D continues up to 1100 UTC which is in agreement with GNSS TPW. The thunderstorm was reported at 1200 UTC. Since INSAT-3D retrieval cannot be made over cloudy region, the TPW observation was not available after 1200 UTC.

In case of the event at Kochi city, the grey bar shows the time of occurrence at 0600 UTC of thunderstorm. It was observed from the satellite imageries that initial convection development starts at 0100 UTC. INSAT-3D TPW is showing the higher TPW values around 58 mm in comparison with GNSS TPW of 51 mm at 0100 UTC. The TPW observation was not available after the 0300 UTC due to cloudy conditions. The higher TPW of INSAT-3D continues up to 0300 UTC in agreement with GNSS TPW and thunderstorm was observed at 0600 UTC.

At 0000 UTC of thunderstorm over Dibrugarh city was reported. The initial convection development started at 1800 UTC with values around 53 mm in comparison with GNSS TPW of 58 mm at 1800 UTC. It can be very well seen from Figure 7, dive has noted at 1400 UTC with values 24 mm from 50 mm. This is due to less precipitation occurred in Dibrugarh while 1400 to 1800 UTC, no precipitation has noted due to cloudy sky. The higher TPW of INSAT-3D continues up to 2000 UTC which is in agreement with GNSS TPW. The thunderstorm was reported at 0000 UTC on June 9, 2017.

The case studies show that during the thunderstorm events, INSAT-3D derived TPW compares reasonably well with GNSS TPW observations, indicating the potential of INSAT-3D derived TPW for the studies on thunderstorm events. Along with other meteorological parameters (e.g., CAPE; convective available potential energy), higher TPW observed during thunderstorm events can be utilized for studying such events. However, the above case studies confirms the usefulness of INSAT-3D derived TPW prior to the event and it can be considered as one of the precursors for mesoscale activity.

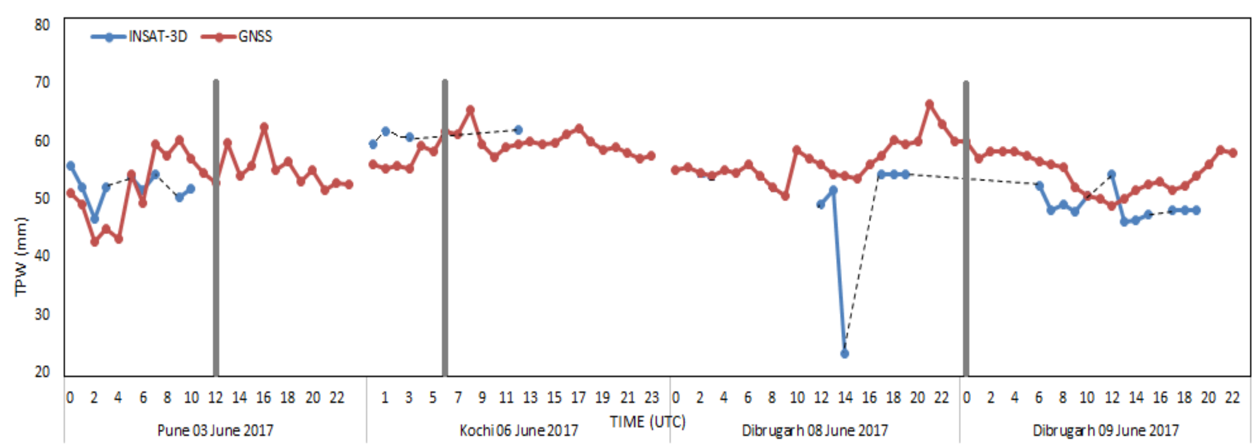

Figure 7. A thunderstorm weather event in Pune on 03.06.2017, Kochi on 06.06.2017 and Dibrugarh on 08-09.06.2017

5. CONCLUSION

In the present study, we have assessed the retrieval performance of INSAT 3D derived TPW by comparing it with corresponding observations from RS network and NOAA also GNSS network over the Indian sub-continental. The comparison carried out at daily, monthly and sub-divisional scale covering south Asian monsoon season with different geographical region of the entire Indian sub-continent. The INSAT-3D derived TPW are in good agreement with the TPW derived from *in-situ* measurement (RS) and NOAA satellites. The RMSE and CC found to be around 8 mm and ~ 0.8 in comparison with RS TPW on daily and monthly basis. On sub-divisional scale as a whole, the RMSE and CC against RS and NOAA TPW, found to be 0.80; 0.90 mm and 1.2; 0.91 mm respectively. It is to be noted that the INSAT-3D TPW on monthly scale shown very good agreement with the sub divisional scale rainfall observations. In addition to that, the comparison of INSAT-3D TPW with actual rainfall observation were also made during the same period. It was observed that the heavy and heavy to very heavy rainfall are corresponding well with the higher TPW values. This indicating the reliability to use the TPW product in forecasting advancement of monsoon precipitation over the Indian region. The improvement observed in the current INSAT-3D sounder products TPW is mainly attributed to the GSICS bias corrections applied to the sounder radiances at IMDPS by SAC/ISRO. The advantages of INSAT 3D TPW product offers real time availability over the Indian region with higher spatial (resolution 10 km) and temporal resolution (60 minute) compared to the other derived from polar orbiting satellites. The quality of TPW product of INSAT-3D shows the potential for its usefulness in weather monitoring and forecasting purpose for the improvement in nowcasting over the Indian region. In future study, INSAT-3D and INSAT-3DR derived TPW in staggering mode (every 15-minutes) can be utilized for the detection and the study of mesoscale activity like thunderstorm during pre-monsoon and monsoon season.

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