Potential of INSAT-3D Sounder Derived Total Precipitable Water Product forWeather 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 sounderis 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 radiance 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 National Oceanic and Atmospheric Administration (NOAA) N-18 and N-19 satellites. To assess retrieval performances of INSAT-3D sounder, RS observations carried out 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 above 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 quantitiesin 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. Kuo et al., (1996) have shown the significant improvement in precipitation forecasts when TPW is incorporated in the numerical weather prediction models. 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 presentstudy, 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. DATA BASE

2.1 INSAT-3D Sounder Scan processing strategy in IMD

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. INSAT3D 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 $18^{\circ} \times 18^{\circ}$ 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 0.1s 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 1996a). The INSAT-3D sounder scan strategy can be used for nowcasting and NWP (Numerical Weather Prediction) model assimilation over Indian region.

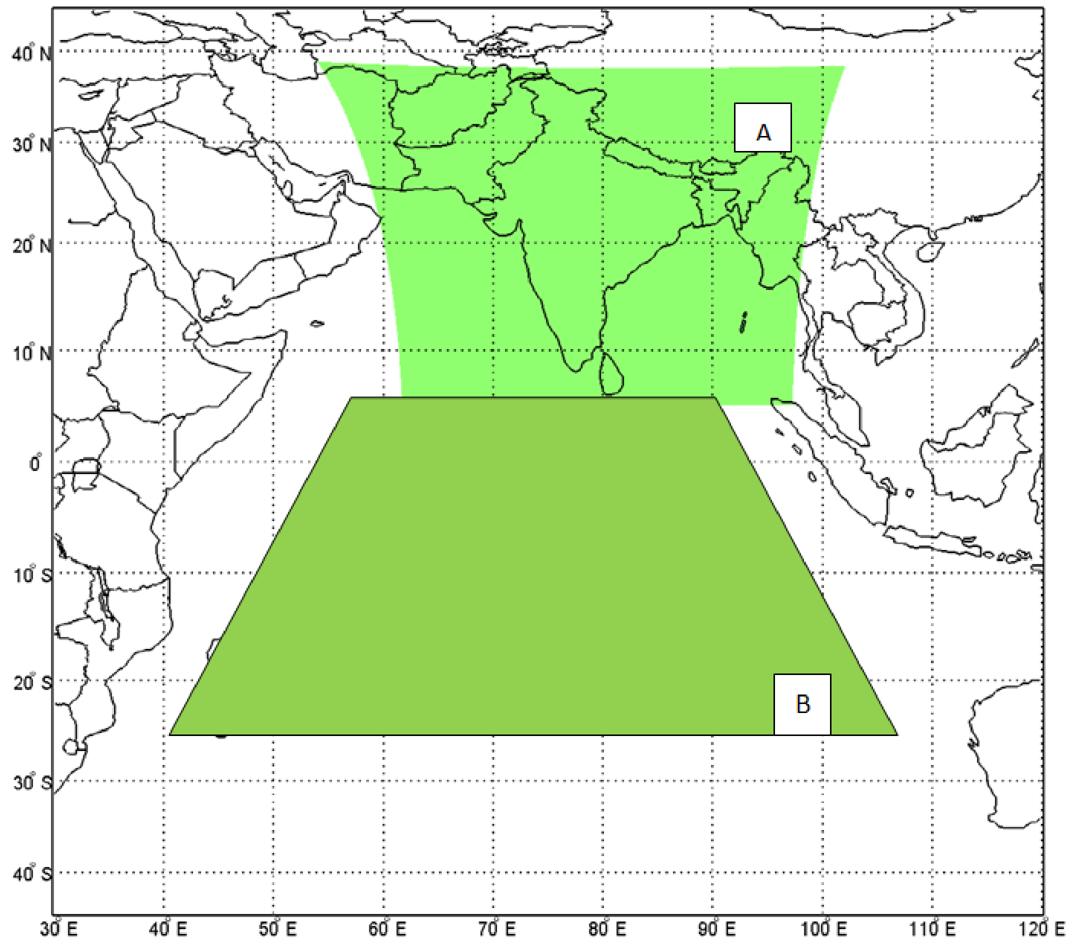


Figure 1. INSAT-3D Sounder scan processing strategy over land and ocean.

2.2 Radiosonde Observations (RS)

In IMD, upper air observations are made at 43 RS stations, 34 RS stations are being usedand 62 Pilot Balloon observatories to provide pressure, temperature, humidity & wind at various levels in the atmosphere up to an altitude of 30-35 kms. 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 by Gajendra Kumar et al., (2011).

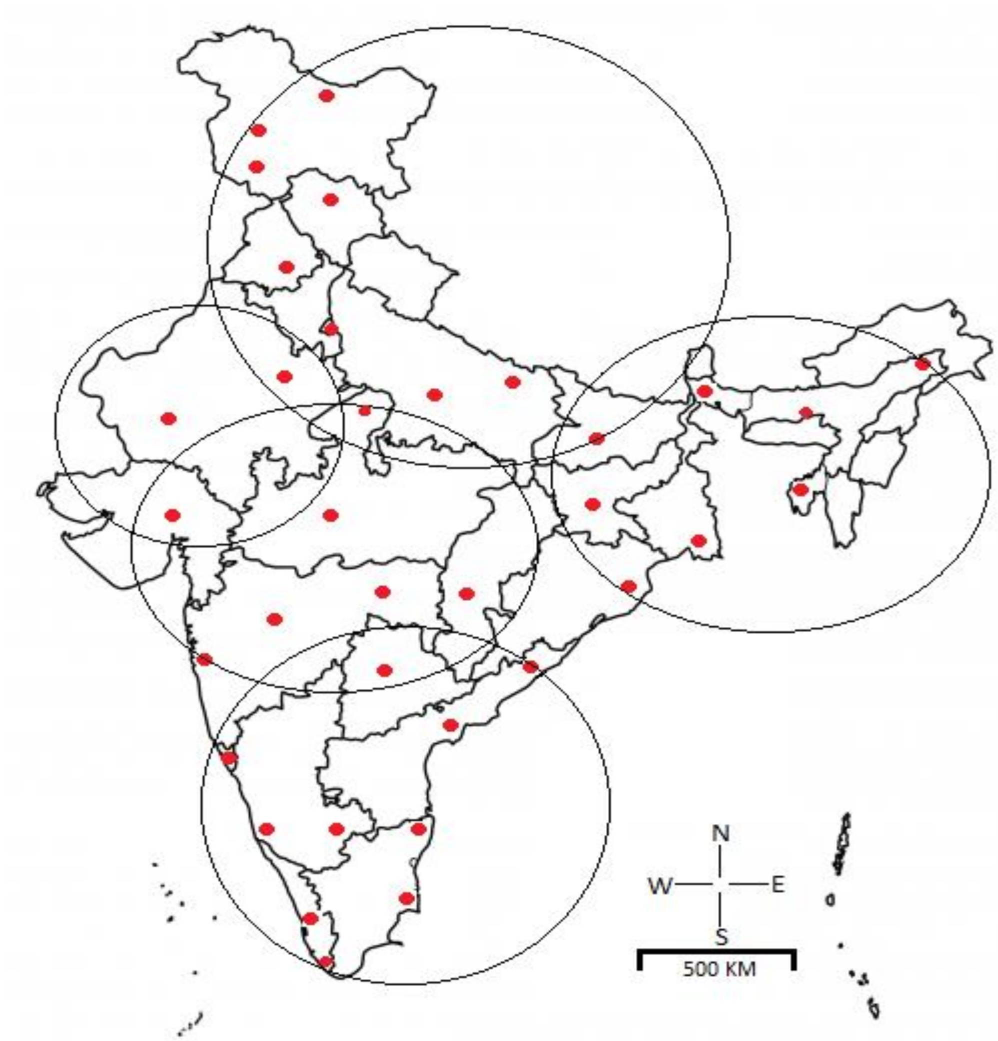


Figure 2. Radiosonde Stations of IMD over India

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. (http://gnss.imd.gov.in/TrimblePivotWeb/)

2.4 NOAA’s satellite observation

NOAA's (Oceanic and Atmospheric Administration) National Environmental Satellite Data and Information Service works for the global community working on weather phenomenon. Advanced Microwave Sounding Unit (AMSU) was aboard in the National's (NOAA) polar orbiting satellites N-18 & N-19. TPW data for the study period was from www.nnvl.noaa.gov.in.

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. 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; 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 acceleration of gravity. 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 Comparisonof INSAT-3D with RS and NOAA TPW at Daily, Monthly and Sub divisional Scale

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).

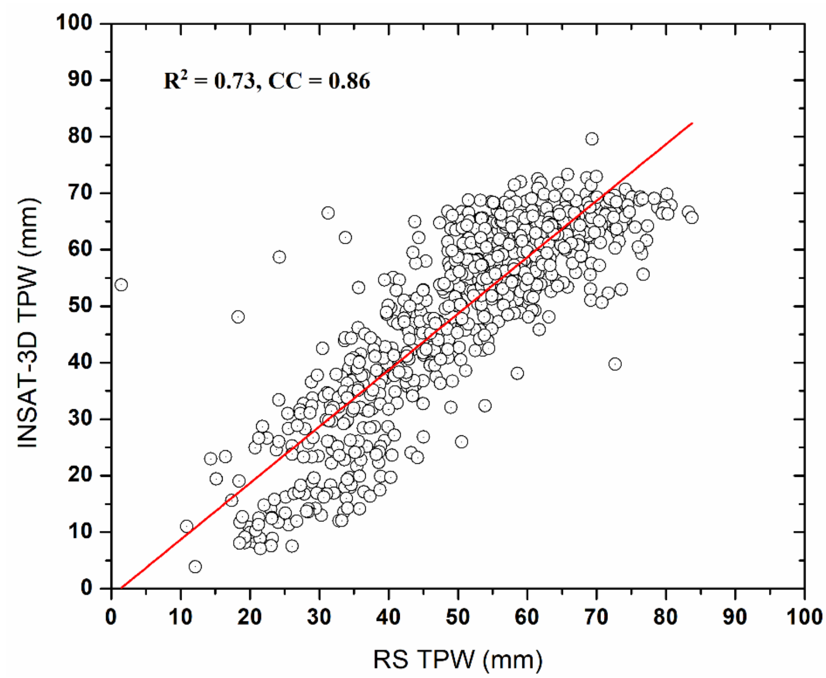
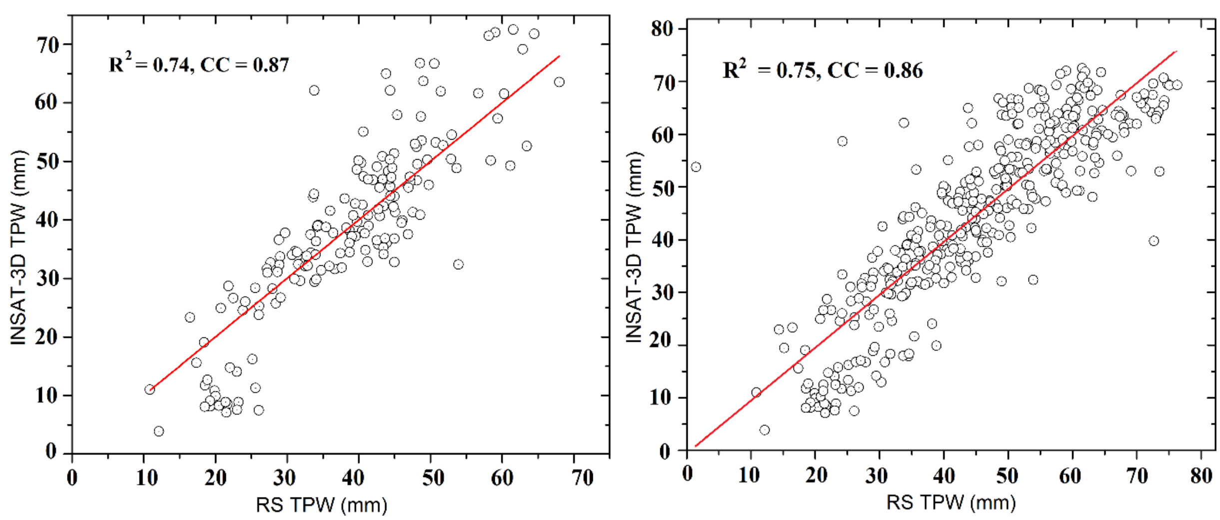


Figure 3. INSAT-3D sounder TPW with RS for Day-wise from May to September 2016

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. The consistent and better correlation has seen above 40mm of TPW values, whereas for less than 40 mm TPW values, INSAT-3D underestimates slightly. This may be attributed to seasonal variation, orographic of the region and different climatic zone over India. The overall correlation on daily scale was found to be 0.86. In the previous study, Mitra et al. (2015) have 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 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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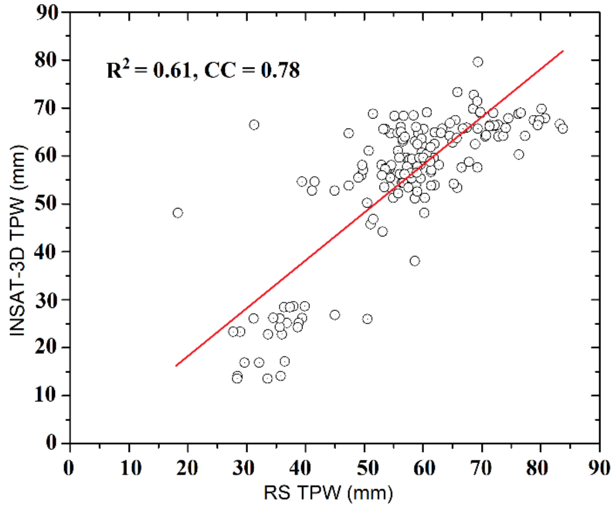

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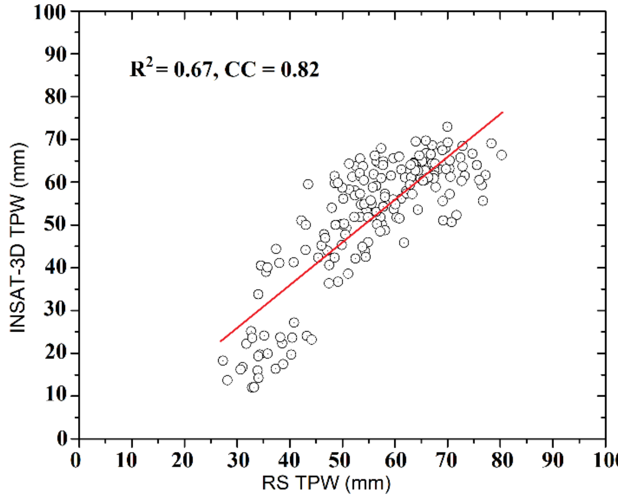

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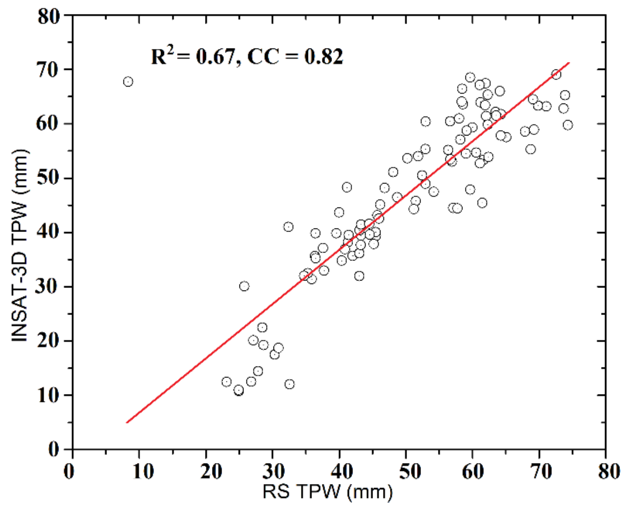

(e)

Figure 4. INSAT-3D sounder TPW with RS for (a) May (b) June (c) July (d) August and (e) 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		Standard		Coefficient		Coefficient				

	Mean (mm)		Deviation		of Variation		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. 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 show good agreement between INSAT-3D and NOAA (0.96) as well as between INSAT-3D and RS (0.87) during June to September, 2016.

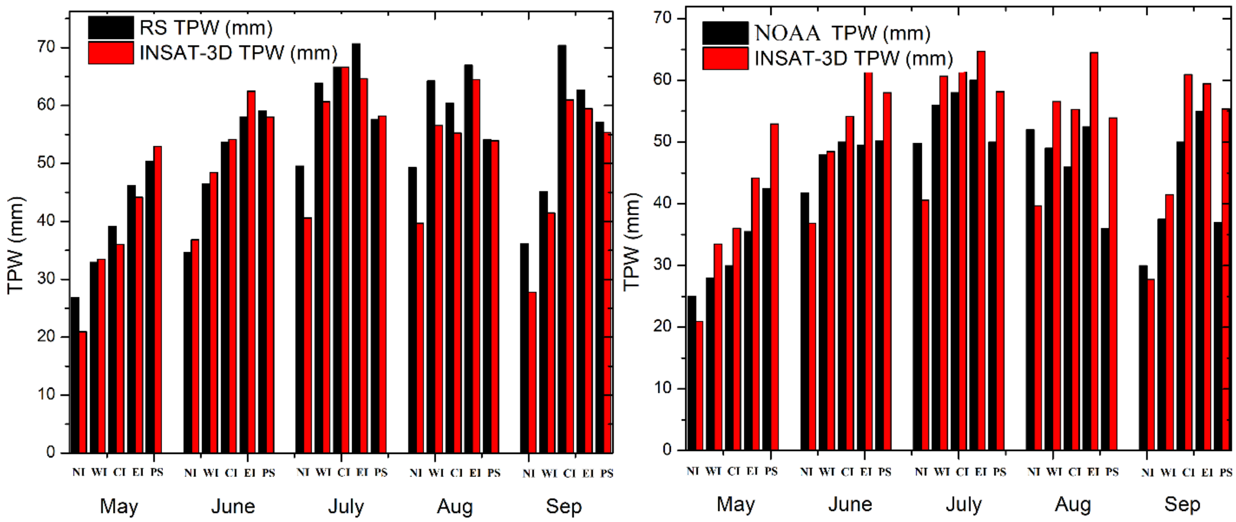

Figure 5. Subdivision wise NI, WI, CI, WI & PS from May to September 2016 between INSAT-3D and RS (left), NOAA (right)

Table 3. Statistics for total precipitable water measured by INSAT-3D, RS and NOAA sub divisional regions 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 spatially analyzed INSAT-3D TPW with Actual Rainfall Observation

Figure 6, shows the comparison of rainfall and TPW for different INSAT-3D TPW values during June to September 2016. This figure is constructed from the daily rainfall observation between 0 to 140 mm occurring over the stations and collocated mean INSAT-3D TPW values between 0 to 90 mm. It can be seen from the figure 6, that higher rainfall amount is accounted with higher INSAT-3D TPW values. 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 rainfallare corresponding to the higher TPW values (60-80 mm and above 80 mm). 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 due to its orography during the summer monsoon season. 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 airmass is transported over the regions. 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.

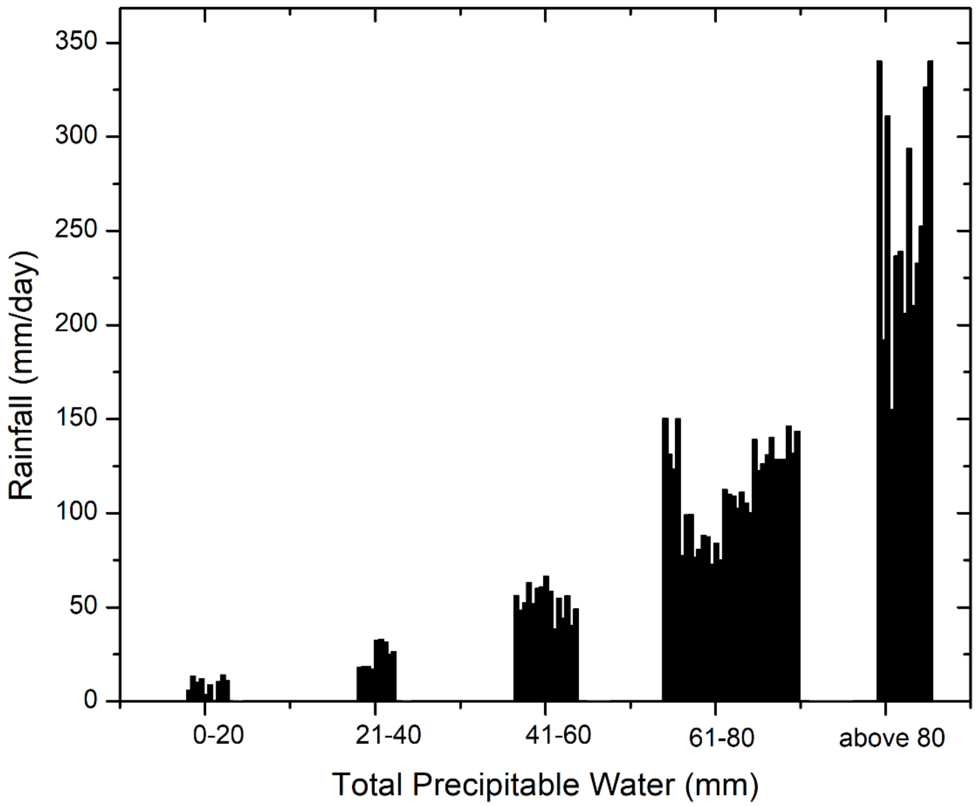

Figure 6. Overall comparison of rainfall with INSAT-3D TPW

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, lat/lon 18.52°/73.85° on 03.06.2017 at1200 UTC, Kochi, lat/lon 9.93°/76.26° on 06.06.2017 at 0600 UTC and Dibrugarh lat/lon27.47°/94.91° on 09.06.2017 at 0000 UTC. The advantage of GNSS is having access to multiple satellites, redundancy and availability at all times.

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 1800UTC with values around 53 mm in comparison with GNSS TPW of 58 mm at 1800 UTC. 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 09.06.2017.

This shows that during the thunderstorm events, INSAT-3D derived TPW compares well with GNSS TPW, showing 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.

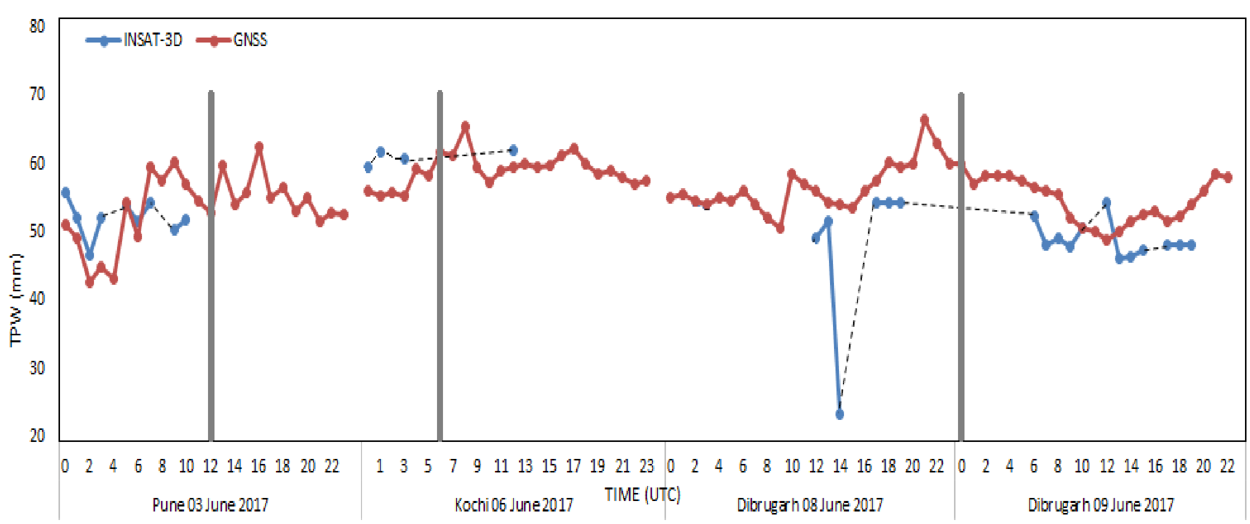

Figure 7. A thunderstorm weather event in Pune on 03.06.2017, Kochi on 06.06.2017 and Dibrugarh on 08-09.06.2017

5. CONCLUSION

In the present study, INSAT-3D sounder derived TPW and corresponding TPW from radiosonde (RS) observations, National Oceanic and Atmospheric Administration (NOAA) N-18 and N-19 and Global Navigation Satellite System (GNSS) receiver network have used to assess retrieval performances of TPW product of INSAT-3D sounder. The comparison carried out at daily, monthly and sub-divisional scale covering the entire South Asian monsoon season with different geographical region of the Indian sub-continent. The INSAT-3D derived TPW are in good agreement (correlation coefficients ~ 0.8) with the TPW derived from in situ measurement (RS) and other satellites. It is to be noted that the INSAT-3D TPW on monthly scale show very good agreement with the sub divisional scale rainfall observations; indicating the reliability to use the TPW product for the advancement of monsoonal pattern over 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 are the availability of the real-time data over the Indian region due to higher spatial and temporal resolution as compared to polar orbiting satellites. The quality of TPW product of INSAT-3D shows the potential for its usefulness in weather monitoring, forecast purpose and also for the improvement in nowcasting. In addition, TPW can also be utilized for the study of mesoscale activity like thunderstorm.

ACKNOWLEDGMENTS

Authors are very much grateful and rendered by Director General of Meteorology Dr. K. J. Ramesh, and given valuable suggestions. We specially thank C.M Kistawal and P. Thapliyal for the improvement of INSAT-3D sounder retrievals specially the applying of the GSICS corrections at IMDPS for the improvement sounder retrievals and their technical inputs. First authors also thankful to NOAA for providing us required data and GSICS members for providing technical support.

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Response to the Referee #1

There is nothing new in the authors findings as INSAT-3d datasets are already validated against with different other datasets at different temporal scales. Also many existing articles are available that shows the importance of water vapor in predicting the storms. The authors neither show any improvements in the retrieval of INSAT-3D TPW nor show its applicability in statistical sense. Thus, I recommend 'Rejection' in its present form. Major concerns:

Referee's comment: The motivation to the work is not clear as Ratnam et al. (2016) as already compared INSAT-3D datasets with other datasets.

Author's response: It is to be noted that the India Meteorological Department (IMD) utilises the INSAT series of satellite data for day to day weather forecast on an operational bases. The timely availability of data is very important for issuing forecasting and nowcasting. To accomplish this on daily, monthly, and sub-divisional scale; satellite derived product is required for users, disaster management group and other services. Over of the period of time, for accuracy of satellite products and its authenticity, a proper calibration is required. In the present work, the GSICS calibration corrections (Global Space-based Inter-Calibration System) on Infra-Red (IR) sounder channels are incorporated at INSAT-3D Meteorological Data Processing System (IMDPS). TPW is derived using this corrected radiance. Subsequently, comparison of TPW with various other dataset is carried out for the validation purpose. This aims to produce corrections, ensuring the data consistency and allowing them to be used to produce globally homogeneous products for environmental monitoring.

In this paper, the analysis and validation justify the usefulness of current TPW product from INSAT-3D which was not exclusively studied by any other past study. Utilization of TPW product from INSAT-3D sounder is mainly in the nowcasting mode, operationally for weather purpose and it can also offer substantial opportunities for improvement in now casting studies. It is to be noted that TPW product utilised in the study incorporates the GSICS calibration corrections.

Referee's comment: How come one time RS observation serves as a representative of daily mean?

Author's response: Twice observations over a day using RS were used for the comparison with daily TPW of INSAT-3D. Indeed, INSAT-3D TPW is not daily mean. Each RS 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 has been considered as 0.5º (50 Km). This will minimize the differences arising from horizontal gradients. (2) The temporal difference between two sets of data is around ±120 minutes depending on retrievals and location of the RS station. (3) The INSAT-3D/RS were matched at 0000 and 1200 UTC (refer line no. 172 to 179).

Referee's comment: INSAT-3D PWV measurements are available only during cloud free conditions then how the authors compared rainfall vs. pwv?

Author's response: We use the mean TPW of INSAT-3D sounder while comparing with the rainfall/rain rate. Rainfall accumulated over a given day is compared with mean TPW of that day, if sky found to be clear over that day. When water vapor reaches to its saturation level in the troposphere, it becomes conducive for occurrence of rain. The higher TPW is expected prior/around the event of rain and vice-versa. Thus, the positive association between TPW and rainfall is obvious. Yes, since only clear-sky TPW is under consideration, there won't be one-to-one correspondence with rainfall. It is the limitation of this comparison.

Referee's comment: Literature survey is very poor.

Author's response: Literature review has been updated (refer line no from 51 to 54).

Referee's comment: With one case study the authors are claimed that high TPW values can be used as a precursor to forecast thunderstorm. Is it true for all the thunderstorm cases as well as all high TPW will lead to thunderstorms?

Author's response: As suggested by the reviewers, two more case study of thunderstorms has been included (refer line no from 274 to 303) in the modified manuscript. It can be seen that most of the thunderstorms analysis have good signature prior to the occurrence of weather events. This can be mentioned here that, IMD (Forecasters, FDP Storm, http://nwp.imd.gov.in/fdp_now/) is regularly utilizing these data in pre-monsoon season for nowcasting services over the Indian region. It was a mistake to consider higher TPW as a precursor to forecast thunderstorm. But along with other meteorological parameters (e.g., CAPE), higher TPW observed during thunderstorm events can be utilized for studying such events.

Referee's comment: The English is also very poor and difficult to follow.

Author's response: The English correction is made and authors think that the manuscript is improved significantly.

Response to the Referee #2

Paper entitled: 'Potential of INSAT-3D Sounder Derived Total Precipitable Water Product for Weather Forecast', this study showed validation of the INSAT-3D satellite derived product total precipitable water (TPW) dataset with radiosonde (RS), NOAA derived TPW, rain measured by rain gauges and one case study using Global Navigation Satellite System (GNSS). This work has done with different temporal scales and area with statistics. Study represents the capability of INSAT-3D sounder derived product and benefits for weather forecasting. Interesting to see that applying of GSICS correction to the sounder retrievals has impacted in the improvement of TPW products. INSAT-3D is geostationary satellite with first time sounder payload facility, keep in mind with this regard, this paper work is contiguous idea within the scope of Atmospheric Measurement Technique Journal. I recommend for publication but the following points have to illustrate my concern:

Referee's comment: Give full abbreviation of IMDPS in abstract and PB section 2.2.

Author's response: This has been corrected from line no. 16 to 17 and 107 to 108.

Referee's comment: In section 2.4, Is GISCS is providing any coefficients? Author should provide clear information about this.

Author's response: Yes. GSICS coefficients generated and corrections applied by Space Application Centre (ISRO), Ahmedabad. The corrections of GSICS coefficients are routinely applied at IMDPS, New Delhi for derivation of the products of INSAT-3D satellite and TPW is one of such product. Refer line no. from 140 to 148.

Referee's comment: In section 3., Has 50km square area been considered?

Author's response: We have considered 50 km around the area from the Radiosonde Station place. In this methodology, each RS was paired with closest INSAT-3D retrievals and patterned according to criteria suggested in Fuelberg and Olson (1991). The collection criteria for INSAT-3D retrievals with RS data are based on absolute distance between the position (latitude and longitude) of the RS and the INSAT-3D retrievals has been considered as 0.5 (50 km). This will minimize the differences arising from horizontal gradients (Line no from 172 to 179).

Referee's comment: In section 4.1, comparison of INSAT-3D and RS at daily, monthly and subdivional scale then why is not promising over northern Indian region as comparison of southern region of India?

Author's response: The comparison of INSAT-3D and RS over northern Indian region shows correlation coefficient of 0.87 which is comparable to that over southern region of India (i.e. 0.92). There is, indeed, very small difference between the observed correlation coefficient over these two regions. This difference could be attributed to number of points under consideration, averaging effect and uncertainty in the satellite retrieved TPW. (Refer line no 248 to 250, table 3)

Referee's comment: In section 4.2, Comparison of spatially distributed INSAT-3D TPW with Actual Rainfall observation, there should be more detail about the figure 6 that how it has constructed?

Author's response: We use the mean TPW of INSAT-3D sounder while comparing with the rainfall/rain rate following the Wu et al 2003 . Rainfall accumulated over a given day is compared with mean TPW of that day, if sky found to be clear over that day. When water vapor reaches to its saturation level in the troposphere, it becomes conducive for occurrence of rain. The higher TPW is expected prior/around the event of rain and vice-versa. Thus, the positive association between TPW and rainfall is obvious. Yes, since only clear-sky TPW is under consideration, there won't be one-to-one correspondence with rainfall. It is the limitation of this comparison.

Referee's comment: In section 4.3, A case study of INSAT-3D TPW with ground base GNSS TPW has been showed. For the justice of this research (prior to the eventINSAT-3D TPW can be considered as a precursor for mesoscale activity), author should give other case study too. It is strongly recommended that author should give one more case study of similar weather event.

Author's response: As suggested by the reviewers, two more case study of thunderstorms has been included (refer line no from 274 to 303) in the modified manuscript. It can be seen that most of the thunderstorms analysis have good signature prior to the occurrence of weather events. This can be mentioned here that, IMD (Forecasters, FDP Storm,http://nwp.imd.gov.in/fdp_now/) is regularly utilizing these data in pre-monsoon season for nowcasting services over the Indian region. However, It was evident that during monsoon season due to the straticumulus clouds over land region, the TPW sometime under/over estimating the actual rainfall. The orographic and coastal region moisture (due to sea breezes) also not very well picked up by sounder derived TPW because of its coarser resolution. Therefore, along with other meteorological parameters (e.g., CAPE, CINE and other indices), higher TPW can be taken as one of the precursors during thunderstorm events can be utilized for studying such events.