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

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Abstract

INSAT-3D satellite objectives to upgrade the meteorological observation, monitoring of earth surface atmosphere for weather forecasting and disaster warning. The amount of the water vapor present in atmospheric column in the form of total precipitable water (TPW) derived product from atmospheric sounding system is one such weather monitoring capability in the INSAT-3D payload. The current study is based on INSAT-3D satellite sounder derived TPW and corresponding TPW from radiosonde observations (RS) and National Oceanic and Atmospheric Administration (NOAA), N-18 and N-19 have been used to assess retrieval performances. The RS TPW from 34 India Meteorological Department (IMD) stations over the Indian region from May to September 2016 has been considered for the validation. The analysis is performed on daily, monthly, sub-divisional and overall basis over the Indian region. On daily and monthly scale against RS TPW, the root mean square error (RMSE) and correlation coefficients (CC) of INSAT-3D TPW are in and around of 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. Furthermore, a case study with INSAT-3D TPW and ground based Global Navigation Satellite System (GNSS) receiver network have been demonstrated. It is noticed that, INSAT-3D TPW can be considered as a precursor for mesoscale activity very well.

The purpose of this study is to investigate the potential use of operational INSAT-3D sounder derived TPW to weather forecast. However, the major source of improvement in INSAT-3D TPW is mainly applying the GSICS calibration corrections (Global Space-based Inter-Calibration

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31 System) on Infra-Red (IR) sounder channels at IMDPS, New Delhi, which aims to produce

32 corrections, ensuring the data consistency and allowing them to be used to produce globally

33 homogeneous products for environmental monitoring. The current TPW from INSAT-3D satellite

34 can be utilized operationally for weather purpose and it can also offer substantial opportunities for

35 improvement in now casting studies.

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

37

1. INTRODUCTION

39 Water vapour is one of the most variable characteristics of the atmosphere. It is an essential factor

40 in climate and weather. It regulates air temperature by absorbing thermal radiation both from the

41 Sun and the Earth; it is directly proportional to the latent energy available for the generation of

42 storms; and it is the ultimate source of all forms of condensation and precipitation. Total

43 Precipitable Water (TPW) Vapor data are potentially significant for weather and climate modeling

44 and prediction. Kuo et al., (1996) found significant improvement in precipitation forecasts when

45 TPW data are assimilated in numerical weather prediction models. Yuan et al., (1993) simulated

46 the utilization of TPW data in monitoring global and regional climate change and found up to 8

47 mm increment in tropical TPW resulting from doubling of atmospheric CO_2.

48 TPW which may be monitored from meso-scale to large scale convective activity and its relation

49 to synoptic circulation systems such as Thunderstorm, monsoonal activities, asymmetries and

50 moisture gradients that aid in interpreting tropical cyclones interaction with dry/moist air by high

51 convective cloud bases. It is the source of the latent heat which is released into the atmosphere

52 during cloud formation. It also dominates the structure of diabatic heating of the earth's

53 atmosphere (Trenberth et al., 2005; Trenberth and Stepaniak, 2003a, b). These parameters vary in

54 time and as well as in space (both vertically and horizontally) throughout the atmosphere. In global

55 atmospheric analyses, the problems come with spatial and temporal gaps. They were impossible

56 to use for climate purposes owing to the huge discontinuities in time as the inevitable

57 improvements were incorporated into the analyses (Trenberth and Olson 1988). This could be

58 possible with accurate temperature and moisture profile either from in-situ observations or

59 remotely sensed data for weather forecasting and nowcasting purposes.

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60   The INSAT-3D satellite imager and sounder products major play role in weather monitoring and

61   provides new understanding of the atmospheric process for monitoring weather. Especially vertical

62   profiles of temperature, humidity and ozone content in atmosphere. It improves analytical skill for

63   weather forecasters. However, the INSAT-3D sounder data is being derived for generally clear sky

64   conditions (Ratnam et. al., 2016). Its wide variety of products such as Geopotential height which

65   can be used to analyze the structure of the convective system TPW, can provide details about

66   mesoscale phenomena and tropical cyclone structure, eg. Symmetries and moisture gradients that

67   aid in interpreting tropical cyclones interaction with dry/moist air.

68   In this study, the INSAT-3D sounder TPW product was statistically compared with radiosonde

69   observations and NOAA satellite data over the period May–September 2016. The purpose of this

70   comparison is to investigate the potential use of operational hourly derived INSAT-3D sounder

71   TPW for monitoring of particularly on severe weather phenomenon over the Indian region.

72   However, initial work using INSAT-3D sounder data has been done by Mitra et al. 2015, who

73   compared INSAT-3D data obtained at 10 RS stations of IMD and Ratnam et al. 2016, using 34 RS

74   observations and compared with data from other satellites like AIRS, MLS and SAPHIR and

75   from ERA-Interim and NCEP re-analysis data sets. Which concludes that INSAT-3D provides

76   measurements with very good spatial and temporal coverage over India compared to any other

77   satellites. It is found that there is a large difference between INSAT-3D and other data sets

78   both in temperature and water vapour above $25\degree$N latitude perhaps due to their geometry. In

79   the present paper, we extended the work with 34 RS stations and taking NOAA data on daily,

80   monthly, sub divisional scale followed by a case study with IMD installed network of GNSS TPW.

81   Furthermore, the spatial distribution of INSAT-3D TPW with actual rainfall observation has also

82   been investigated.

83   **2. DATA BASE**

84   **2.1 INSAT-3D Sounder Scan strategy in IMD**

85   *2.1.1 INSAT-3D Sounder Specification*

86   INSAT-3D sounder is advance weather satellite with improved imaging system and atmospheric

87   sounder. INSAT-3D sounder generating vertical profile of the atmosphere in terms of temperature

88   and humidity. INSAT-3D payloads such as sounder is first time introduce in ISRO satellite

89   mission. INSAT3D sounder has one visible spectral channel and eighteen channels in shortwave

90   infrared (SWIR), middle infrared (MIR) and long wave infrared (LIR) regions. For all channels

91   ground resolution is 10x10km. The INSAT-3D sounder detail can be found on Mitra et.al, 2015.

92   **Table 1Sounder 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

93   *2.1.2 INSAT-3D Sounder Scan Strategy*

94   INSAT-3D retrieval algorithm at IMDPS, New Delhi is designed for retrieving vertical profiles of

95   temperature and moisture from radiances in 18 channels. National Center for Environment

96   Prediction (NCEP) Global Forecast System (GFS) consisting of 12 hour forecast, retrieval

97   algorithm has taken for first-guess input. On account of its higher temporal as well as horizontal

98   resolution, these retrievals provide the significant data on vertical structure of the atmosphere over

99   land and oceanic region. Currently, these information are being obtained from conventional in-situ

100 based methods of observations. INSAT-3D retrieval algorithm is based on clear sky infrared

101 radiances, which includes different absorption bands observed through sounder all channels on an

102 hourly time scale. In the scheme, computation of the hybrid first guess atmospheric profiles using

103 a linear combination of regression retrieval and NWP model forecast are being used (Mitra et al.,

104 2015). The methodology has followed by non-linear physical retrieval procedure (Li et al., 2000;

105 Ma et al., 1999) for first guess consistent with the sounder observations. The another methodology,

106 pressure layer fast algorithm for atmospheric transmittance (PFAAST) radiative transfer model

107 (Hanon et al., 1996) has used for the forward computation of sounder channel radiances along with

108 the Jacobians, which is used in the physical retrieval.

109 Figure-1 shows that every hour over Indian land mass (A) and every 6th hour Southern Hemisphere

110 (B), the sounder data is being processed at IMDPS, New Delhi on an operational basis. This is the

111   simplest scanning mode kept in such a way that sounding over larger region (land+ocean) will be

112   available every hour. Full frame mode scan is 18º × 18º North South (NS) covering the entire earth

113   disc in about 25.7 minutes. Program mode - 18º in East West (EW) direction, while NS coverage

114   can be programmed. Sounder completes sounding in 10 km × 10 km area in 0.1s and performs

115   space look operation once every 2 minutes. Black body calibration is performed in every 20

116   minutes or on command. INSAT-3D Sounder have a capability to scan in the steps of 64 × 64

117   pixels. Scanning of a region covering 640 × 640 pixels that is roughly 6400 km × 6400 km will

118   take about 180 minutes. This implies that the one step of 64 × 64 will take approximately 1.8

119   minutes. The INSAT-3D provides hourly observations over Indian landmass and every 6-hour

120   observations over Oceanic region. The uncertainties can occur in quantitative accuracy in the

121   precipitation estimation during nonsummer seasons, where convective precipitation is not

122   dominant (Arkin and Xie 1994). This benefits of these kind of scan strategy is best utilize for the

123   studies of initial convections and genesis of evolution of squall lines and there fine structure

124   (Purdom 1996 a). Therefore, INSAT-3D sounder scan strategy can be used for nowcasting and

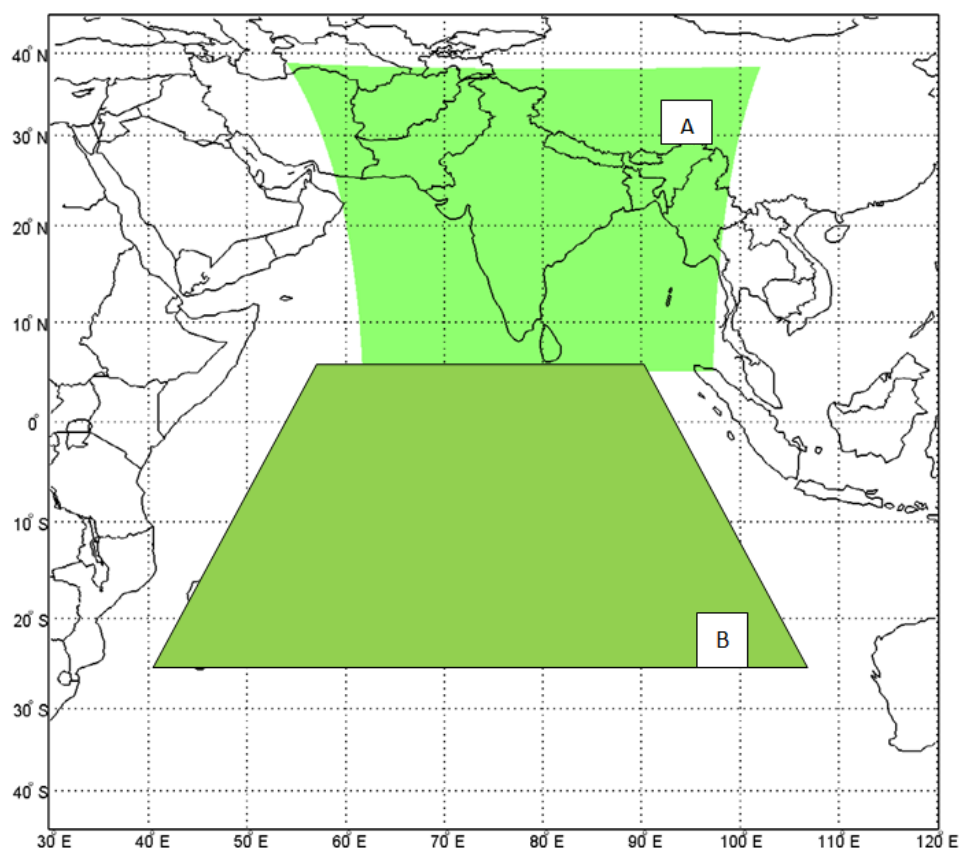125   NWP model assimilation over Indian region.

126

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

128 **2.2 Radiosonde Observations (RS)**

129 In IMD, upper air observations are made at 43 RS/RW stations, 34 RS/RW stations are being used

130 and 62 Pilot Balloon observatories to provide pressure, temperature, humidity & wind at various

131 levels in the atmosphere up to an altitude of 30-35 kms for RS/RW and up to a maximum altitude

132 of 18 kms employing optical theodolites for PB stations. The types of ground equipment used in

133 RS observatories have been equipped with three types of ground equipment as under;-

134 • Radiosonde Ground equipment (ECIL/DIGITAL make) along with X band Win

135 • d finding Radars (EEC/MULTIMET) at 401 MHz

136 • IMS-1500 Radiotheodolite at 1680 MHz

137 • SAMEER Radiotheodolite at 401 MHz

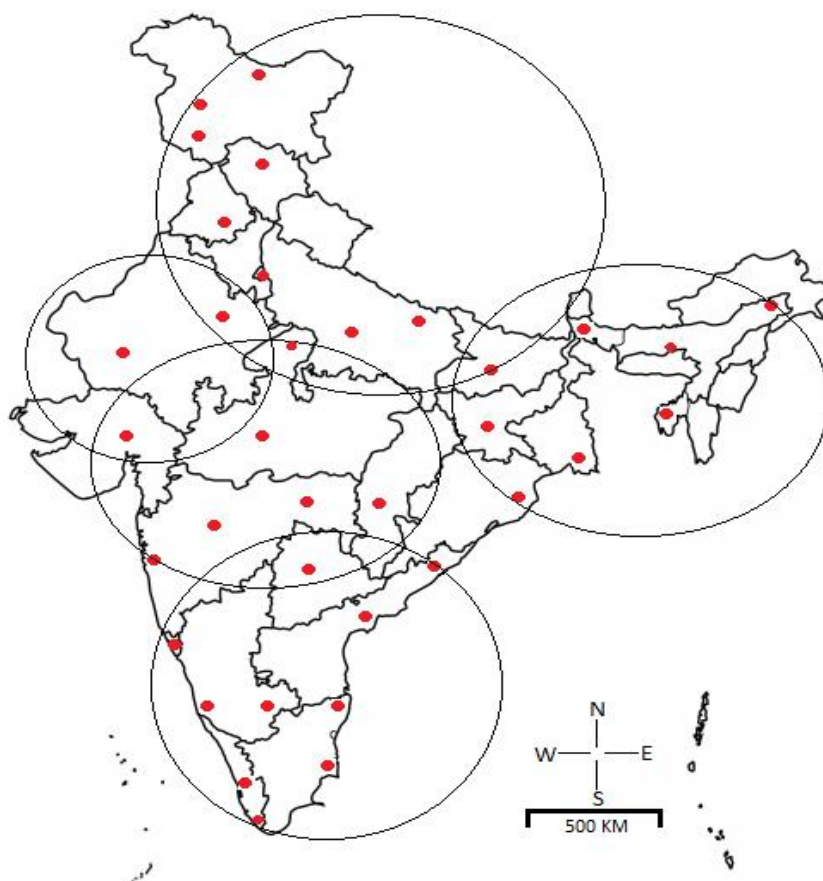Atmospheric
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Figure 2. Radiosonde Stations of IMD over India

140   Over all 34 RS stations marked in red color in Figure-2 is taken for the comparison with INSAT-

141   3D TPW.

142   **2.3 NOAA**

143   NOAA's National Environmental Satellite Data and Information Service works for weather

144   community launched Advanced Microwave Sounding Unit (AMSU) was aboard in the National

145   Oceanic and Atmospheric Administration's (NOAA) polar–orbiting satellites. The first AMSU–A

146   was launched on the NOAA–15 satellite on 13 May 1998. NOAA real time data have been

147   downloaded from www.nnvl.noaa.gov.in.

148   **2.4 GSICS based inter-calibration**

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149 There is an on-board blackbody which is responsible for generation of calibration information
150 for all the IR channels in Imager and Sounder payloads. In-orbit readings of blackbody precision
151 temperatures revealed a gradient among the sensor readings which led to inaccuracy in getting
152 the correct blackbody temperature. It was also observed that during satellite midnight, sun-rays
153 from behind the earth enter directly into the sensor and hence lead to increase in blackbody
154 temperatures. This phenomenon also leads to incorrect calibration information generation. In order
155 to provide climate quality products and to improve the calibration information quality
156 GSICS   based   inter-calibration   is   used   for   INSAT-3D/3DR.
157 Thus the channel wise GSICS coefficient found out are absorbed in the Radiometric Correction
158 process. These coefficients are applied on the channel-wise radiances found out by
159 using in-orbit calibration information in the retrieval process.

160

3. METHODOLOGY

162 INSAT-3D retrieval algorithm at IMDPS, New Delhi, is designed for retrieving vertical profiles
163 of atmospheric temperature and moisture in the atmosphere from clear sky infrared radiances in
164 different absorption bands observed through the various sounder channels on an hourly time scale.
165 India Meteorological Department (IMD), New Delhi, has adapted sounder retrieval scheme from
166 the operational High resolution Infrared Radiation Sounder (HIRS) processing scheme and
167 Geostationary Operational Environmental Satellites (GOES) algorithms developed by Cooperative
168 Institute for Meteorological Satellite Studies (CIMSS), University of Wisconsin, USA (Ma et al.,
169 1999 and Li et al., 2000). In this system, physical and regression based retrievals are employed.
170 Which includes spectral bands in and around the CO_2 and H_2O absorbing bands. These bands
171 having the vertical structure of atmospheric temperature and moisture (Mitra et al. 2015).

172 The Sounder-derived product like Total Precipitable Water (TPW) is the amount of the water vapor
173 present in atmospheric column from the surface of earth to space. Mathematically, if a(p) is the
174 mixing ratio at the pressure level, p, then the INSAT-3D precipitable water vapor W, contained
175 in a layer bounded by pressures p_1 and p_2 is given by

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

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177   Where ρ represents the density of water and g is the acceleration of gravity and can be found in

178   detail http://www.imd.gov.in/INSAT-3D/categouge.

179   In the present study, we are being done RS observations for pairing with their closest INSAT-3D

180   TPW values. The RS observations provide temperature and dew point as functions of pressure at

181   both mandatory and significant levels and these data were obtained from IMD's network. The

182   performance of IMD's GPS radiosonde stations has been very well examined using ECMWF

183   global data monitoring report by Gajendra Kumar et al., (2011).

184   In our evolution methodology, each RS was paired with closest INSAT-3D TPW and patterned

185   according to criteria suggested in Fuelberg and Olson (1991). The collocation criteria for INSAT-

186   3D retrievals with RS and NOAA data are based on the following: (1) The absolute distance

187   between the position (latitude and longitude) of the RS and the INSAT-3D retrievals has been

188   considered as 0.5º (50 Km). This will minimize the differences arising from horizontal gradients.

189   (2) The temporal difference between two sets of data is around ±120 minutes depending on

190   retrievals and location of the RS station.

191   Furthermore, to improve the quality of sounder derived radiances in INSAT-3D, the Global Space-

192   based Inter-Calibration System (GSICS) corrections have been applied to the INSAT-3D sounder

193   radiances on an operational basis at IMDPS, New Delhi. The GSICS aims to inter-calibrate a

194   diverse range of satellite instruments to produce corrections ensuring their data are consistent,

195   allowing them to be used to produce globally homogeneous products for environmental

196   monitoring. GSICS develops common methodologies to check the quality of sensors operated by

197   various satellite agencies over the worldwide. These satellite organizations works for weather

198   forecasting, climate & atmosphere changing and environmental applications. This is post launch

199   calibration strategy which involves spectral response function of sensors, sensor performances and

200   inter-calibration of satellite sensor after that recalibration of archived data or products of sensors.

201

202   **3. RESULTS AND DISCUSSIONS**

203

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

INSAT-3D derived TPW is being derived over Indian region almost every hour. For verification purposes of NWP model derived precipitable water and usefulness in weather forecast. It is desirable to compare INSAT-3D TPW at different time scale with different sets of data. Thus, on a daily scale, we compared the INSAT-3D TPW with all the collocated datasets against RS TPW. On monthly scale, month average data on collocated points were averaged. 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).
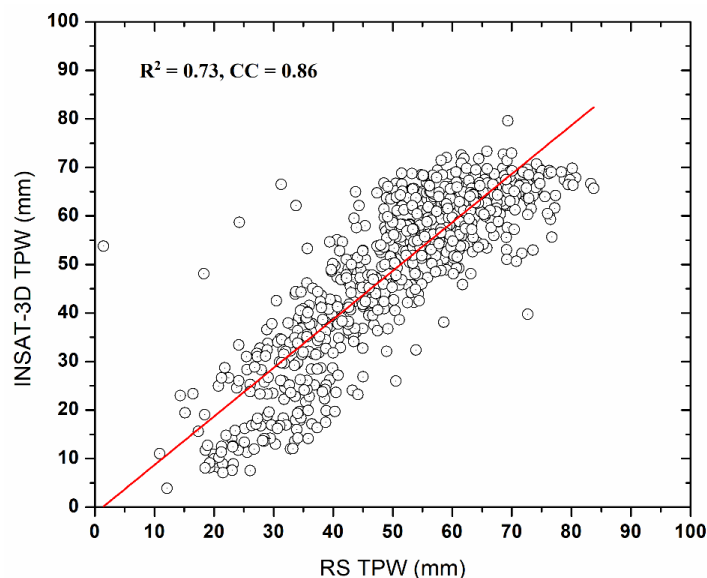

Figure 3. INSAT-3D sounder TPW with RS for Day-wise from May to September 2016

Figure 3 shows the comparison of INSAT TPW and RS TPW on daily scale during May-September 2016. On a day to day basis, INSAT-3D TPW agrees well with RS TPW. There is a consistent correlations noticed above 40mm of TPW values whereas less than 40mm TPW values, INSAT-3D underestimates the RS observations. 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

222   using 10 IMD stations. Figure 4 shows the comparison of INSAT-3D TPW and RS TPW on

223   Monthly scale during May-September 2016. It can be noticed that during monsoon period and

224   specially month of June, July and August, heavy rainfall (above 64.5 mm) occurrence have very

225   well agreement with INSAT-3D TPW values. Mostly INSAT-3D TPW is higher when rainfall

226   occurrence is higher above 40 mm. Monthly correlation was found to be above 0.78.

227   In table 2, INSAT-3D and RS Relation between the standard deviation and the arithmetic mean

228   values indicates that the deviation from the normal distribution cannot be ignored. INSAT-3D

229   coefficient of variation values are high as compared with RS, which indicates that total precipitable

230   water being variable measured by INSAT-3D. The lower the coefficient of variation of TPW

231   amount in July to September, 2017. The Coefficient of skewness values found negative between

232   INSAT-3D and RS measurement, which indicates mean is less than the mode of the data. The

233   correlation coefficient show good agreement with well RMSE for June to September, 2017 except

234   in month of July. The student's t-test has calculated for significance of computed parameter. Which

235   is provided distribution of same is normal for INSAT-3D and RS measured data. This found to

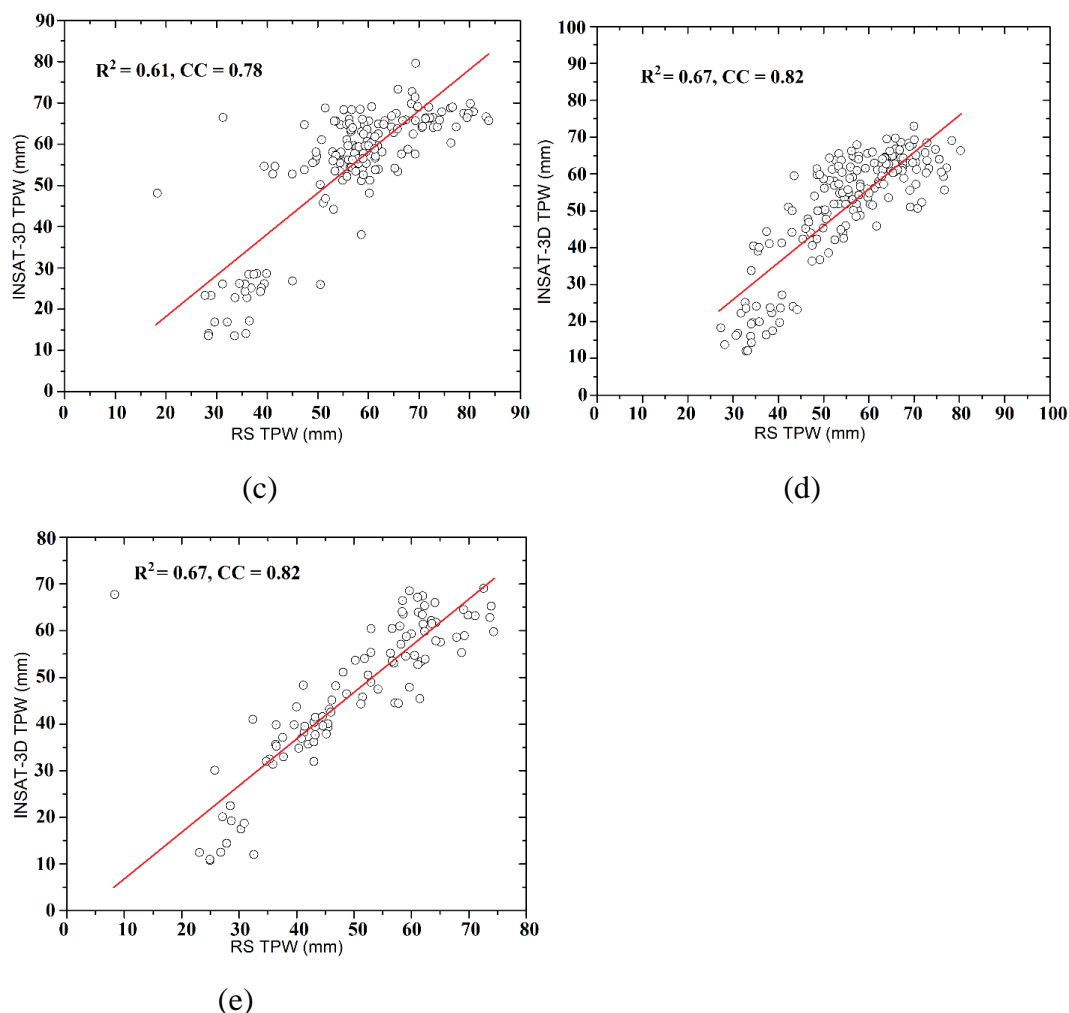236   good fit between, INSAT-3D and RS TPW.

237

238

239   (a)   (b)

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241   (c)   (d)

242

243   (e)
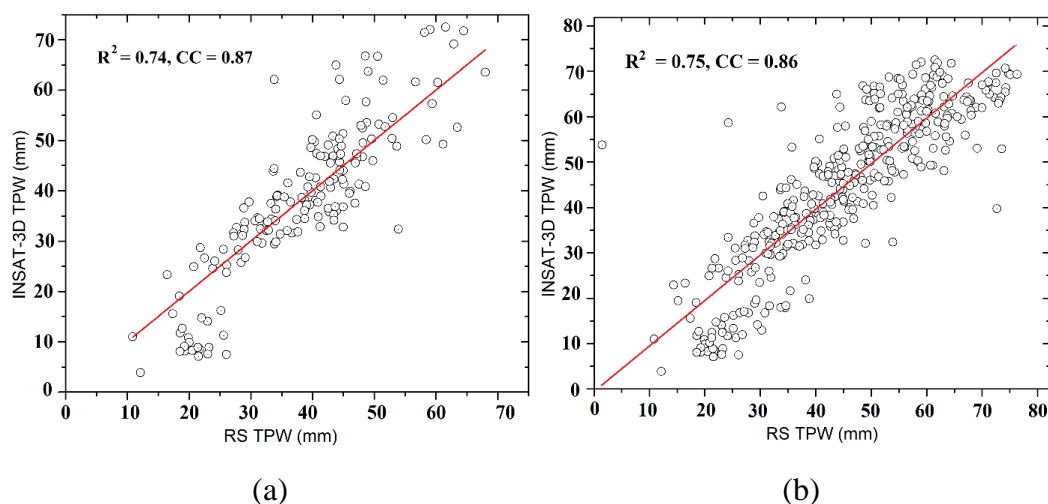
244 **Figure 4. INSAT-3D sounder TPW with RS for (a) May (b) June (c) July (d) August and (e)**
245 **September 2016**

246

247 **Table 2. Statistics and correlation between total precipitable water measured by INSAT-3D**
248 **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

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| 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

249

250 Figure 5 shows the comparison of INSAT-3D TPW with RS and NOAA TPW on sub divisional

251 scale during May-September 2016. It can be clearly seen from the figures that INSAT-3D TPW is

252 under estimating the RS TPW whereas it is over estimating the NOAA TPW for the entire region

253 during the monsoon period. However, the moisture convergence, advection of moisture and

254 geographical locations of the subdivisions, which occasionally receive heavy to very heavy rainfall

255 due to synoptic scale monsoon circulations or orographic area during summer monsoon season

256 plays the major role in the activity of rainfall over the Indian sub-continent. The areas such as high

257 orographic region like north eastern parts and Jammu and Kashmir and parts of Western Ghats in

258 the west coast of India, have less evaporation rates and high rainfall and the moisture laden that is

259 transported into the region could not be fully captured by the satellite observations. Similarly it is

260 also observed that the rainfall is overestimated in the dry conditions because the falling raindrop

261 evaporates before coming to the surface in dry conditions resulting the over estimation while

262 comparing with actual observation. In contrast, CI and PS, have a good correlations compared to

263 EI and NI. However, opposite trend were found while comparing INSAT-3D TPW with NOAA

264 TPW. INSAT-3D TPW is always higher over NOAA data. One of the reasons is that INSAT-3D

265 sounder derived products were calculated from the radiances sampled every hour while NOAA

266 TPW were based on only two satellite passes with equator crossing times of 0230 and 1430 local

267 time. Therefore, TPW derivation methodology is the same whether the radiometer is on polar or

268 geostationary satellite, the sampling frequency of the radiometer is much higher in a geostationary

269 satellite than polar satellite. In general, sub-divisional comparison revels that the INSAT-3D TPW

270 agrees well RS and NOAA TPW below $23\,^{\circ}$N whereas the difference is higher above $23\,^{\circ}$N.

271 In table-3. The standard deviation and the arithmetic mean values indicates that the deviation from

272 the normal distribution, cannot be ignored, which shown deviation according from the data with

273 subdivisions in India for INSAT-3D, RS and NOAA. INSAT-3D coefficient of variation (CV)

274 values are similar with RS, which indicates that total precipitable water being variable, but in case

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275 of NOAA CV found higher with respect to INSAT-3D and RS. The Coefficient of skewness values

276 found negative in case INSAT-3D, RS and NOAA measurement, which indicates mean is less than

277 the mode of the data. The correlation coefficient (CC) show good agreement with well RMSE

278 from June to September, 2017 between INSAT-3D and NOAA found 0.96 and INSAT-3D and RS

279 found 0.87.

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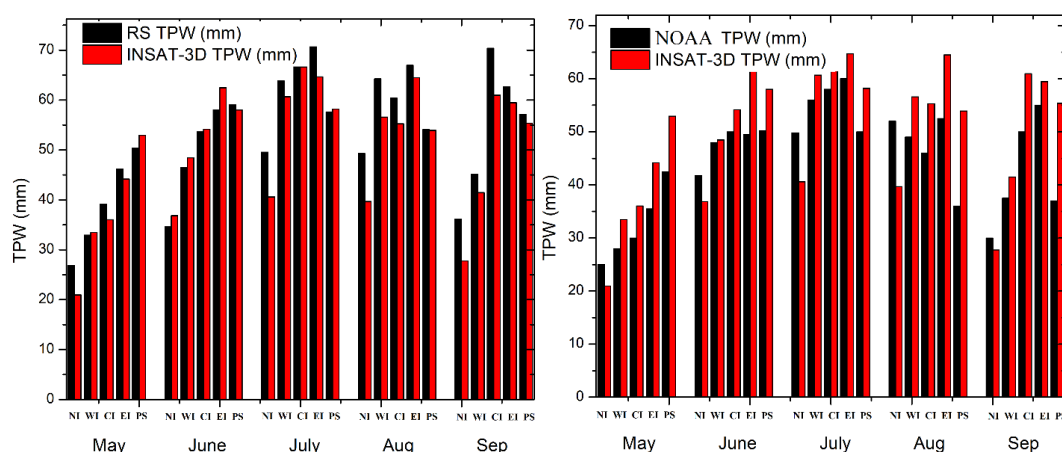
282 **Figure 5. Subdivision wise NI, WI, CI, WI & PS from May to September 2016 between**

283 **INSAT-3D and RS (left), NOAA (right)**

284 **Table 3. Statistics for total precipitable water measured by INSAT-3D, RS and NOAA**

285 **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						
	INSAT-3D	59.05	8.58	0.14	-1.92	-1.71	1.27	0.91	0.37	0.83	0.91
	RS	60.92	9.47	0.15	-1.00						
PS	NOAA	43.14	6.81	0.15	0.10						
	INSAT-3D	55.68	2.36	0.04	0.05	-2.5	1.55	0.77	-0.002	0.45	0.92
	RS	55.66	3.44	0.06	-1.00						

286

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

289

290 Figure 6, shows the overall spatial distribution of rainfall change for different INSAT-3D TPW

291 values during June to September 2016. This figure is constructed for all the daily rainfall amount

292 from actual IMD observation between 0mm to 140 mm occurring over the stations and collocated

293 mean INSAT-3D TPW values between 0mm to 90mm. It can be seen from the figure 6 that higher

294 rainfall amount is accounted with higher INSAT-3D TPW values. However, atmospheric

295 constituents and synoptic scale of monsoon conditions are an important factor when considering

296 the occurrence of rainfall and satellite derived TPW. It is well demonstrated from the figure 6, that

297 the heavy (60-80 mm) and heavy to very heavy rainfall (above 80mm) is very well matching with

298 the higher TPW values. This can be related to the fact that the heavy rainfall occurs in the presence

299 of higher TPW values (Wu et al, 2003). However, for the light to moderate rainfall amount (less

300 than 40 mm) INSAT-3D TPW is not picking up the intensity, this may be attributed to the failure

301 of capturing moisture divergence and subsidence in the lower levels of the atmosphere by the

302 geostationary satellites due to its resolution. The ground resolution of INSAT-3D sounder is

303 10km.These limitations of sounders put the emphasis on high horizontal resolution (better than

304 10km), and on high vertical resolution (about 1km). This will provide frequent information on the

305 3D structure of atmospheric temperature and humidity, for the whole Earth disk seen by the

306 satellite (except in and below clouds). They will be used, together with the imagers, to produce

307 high resolution clouds or water vapour features, to track rapidly evolving phenomena. They are

308 also designed to have an important role in the frequent observation of atmospheric chemical
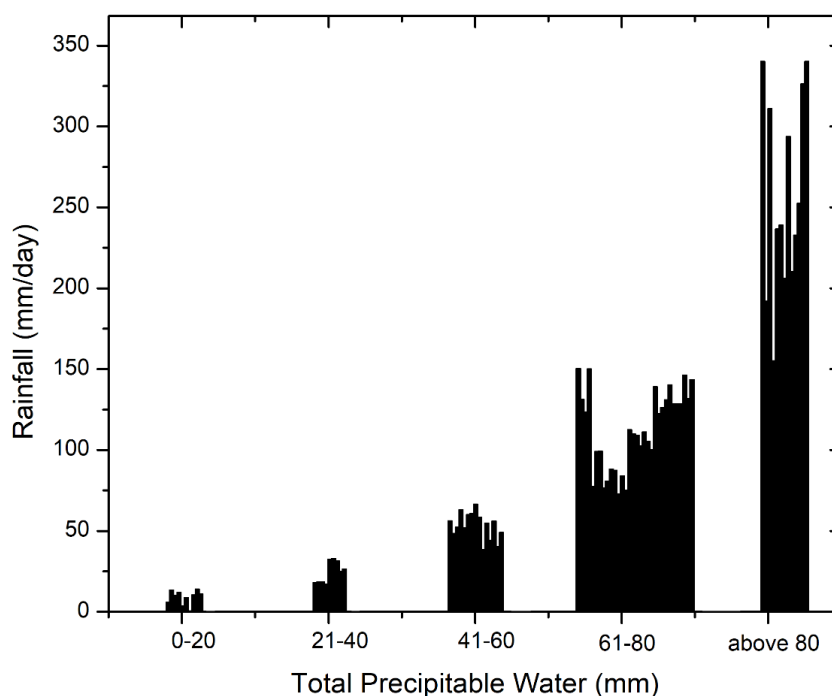
309 composition.

310

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

4.3 A case study of INSAT-3D TPW with ground base GNSS TPW

In this case study, hourly INSAT-3D sounder derived TPW, and GNSS TPW were analyzed for a thunderstorm event occurred at Pune on 03.06.2017 of 1200UTC.The advantage of GNSS is having access to multiple satellites, redundancy and availability at all times. Though satellite systems don't often fail, if one fails GNSS receivers can pick up signals from other systems.

Figure 7, shows the hourly comparison between INSAT and GNSS TPW. The red bar shows the time of occurrence (i.e., 1200 UTC) of thunderstorm over Pune city. It was observed from the satellite imageries that initial convection development starts at 0600 UTC with multiple significant convection seen over the area. 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 with agreement with GNSS TPW. The thunderstorm was reported at 1200 UTC. Since INSAT-3D retrieval cannot be made over cloudy

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326   region, the TPW observation was not available after the 1200 UTC. However, prior to the event

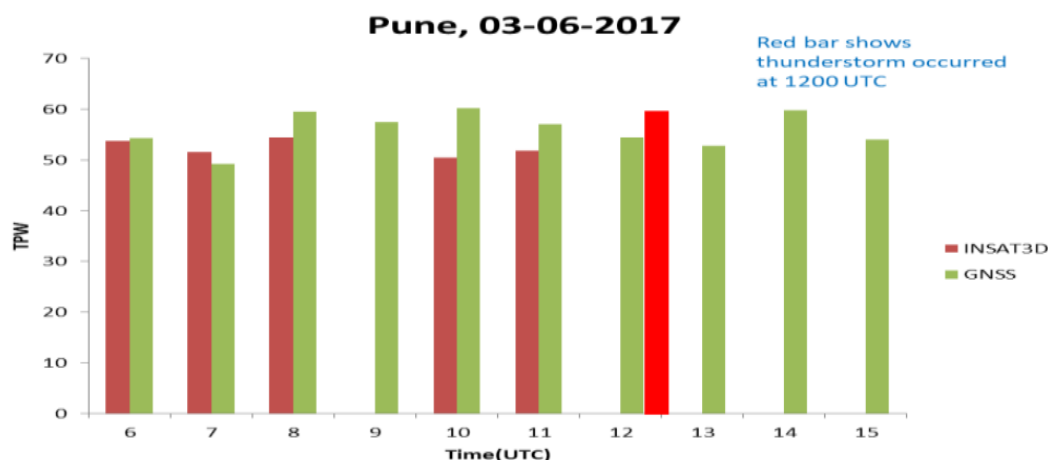327   INSAT-3D TPW can be considered as a precursor for mesoscale activity.

328

329   **Figure 7. A thunderstorm weather event on Pune (18.52°N 73.85°E) on 03.06.2017**

330

331   **CONCLUSION**

332   In the present study, INSAT-3D satellite sounder derived TPW and corresponding TPW from

333   radiosonde observations (RS) and National Oceanic and Atmospheric Administration (NOAA) N-

334   18 and N-19 have used to assess retrieval performances covering the entire season with

335   geographical region over the Indian sub-continent. The INSAT-3D derived TPW has also very

336   well picked the general feature of monsoon at daily as well as monthly scale. Most of the region

337   except north eastern parts and north western region the magnitude is slightly differ. This may be

338   attributed to the orography area of that region as well as geometry. It is also to be mentioned that

339   the INSAT-3D TPW on monthly scale show very good agreement with the sub divisional scale

340   rainfall observational pattern indicating good reliability to use the INSAT-3D TPW for

341   advancement of the monsoonal pattern. The advantages of INSAT-3D TPW are the availability of

342   the real-time data over the Indian region due to higher spatial and temporal resolution as compared

343   to polar orbiting satellites. The quality of the TPW from INSAT-3D wills substantial improves the

344   now-casting as well as the rainfall prediction by assimilating into the NWP model. Furthermore,

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345   the spatial distribution of INSAT-3D TPW with actual rainfall observation is also been

346   investigated and found that heavy rainfall events occur in the presence of high TPW values.

347   The improvement observed in the current INSAT-3D sounder products specifically TPW is mainly

348   attributed to the GSICS bias corrections applied to the sounder radiances at IMDPS by SAC/ISRO,

349   Ahmadabad. This study will provide the reasonable interpretation and quantitative benefit to NWP

350   and can also offer substantial opportunities for improvement in now casting studies.

351

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