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An appraisal of rainfall estimation over India using remote sensing and in situ measurements

Sanjeev Dwivedi[a,b], Manoj Kumar Thakur[c], T V Lakshmi Kumar[d], B M Rao[e], C M Kishtawal[e] & M S Narayanan[d]*

[a]School of Earth, Ocean and Climate Sciences, Indian Institute of Technology, Bhubaneshwar 752 050, India

[b]Meteorological Centre, India Meteorological Department, Bhubaneswar 751 019, India

[c]Department of Physics, Tri-Chandra Multiple Campus, Tribhuvan University, Kathmandu 44 600, Nepal

[d]SRM Institute of Science & Technology, Chennai 603 203, India

[e]Space Application Centre, Indian Space Research Organisation, Ahmedabad 380 058, India

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The most important meteorological parameter Rainfall, shows high variability in space and time, particularly over Tropics / Monsoon region. Many new observational and analysis methods to observe / analyse them by remote sensing techniques (Satellites, Doppler Weather Radars) have emerged over the decades, besides the dense network of in situ rain gauges, Automatic Weather Stations (AWS) etc on ground. The scales of observations being vastly different for in situ and remote sensing methods, large discrepancies between different techniques are inherent. These problems have been brought out through various validation studies by many groups in the country. Even on the daily all India spatial scale, basically only the peaks and troughs from satellite estimates match reasonably well with in situ data. Results of a case study during an intense and long-lasting rain event over Chennai, from DWR, with different satellite products and ground truth are presented. The importance of DWR rainfall data in significantly improving the integrated products is emphasised. A simple two-way approach to establish Z – R relationship for the DWRs in the country is also suggested. A well-coordinated integrated programme to study the inter comparability of precipitation at various spatio- temporal scales in the context of our water resources, model validation, extreme rainfall events, Climate change, etc., is called for. The desired accuracies from satellite data vis a vis IMD gridded data for different applications have been summarised.

Keywords: Monsoon rainfall, India Meteorological Department (IMD4) gridded data, INSAT (Indian National Satellite), Tropical Rainfall Monitoring Mission (TRMM), Global Precipitation Mission (GPM), Integrated Multi-satellite Retrievals for GPM (IMERG), Doppler Weather Radars (DWR), Z–R relation

1 Introduction

Accurate measurements of precipitation and their variability are important for our country, not only for management of water resources, but also to understand the coupling of Earth's water, energy, and bio - geochemical cycles. Variability of Monsoon rainfall, both in intra-seasonal and inter-annual scales plays important role in our economy.

Rainfall is traditionally measured by ground based rain gauges over land by almost all nations, though the network may not be sufficient / uniform to account for the high spatio- temporal variability of this parameter, more so in mountainous regions. Only a few measurements over islands have been representative of oceanic rainfall. Other meteorological parameters (like winds, temperature, humidity, pressure etc.) and their space – time derivatives that go as input to Numerical Weather Prediction (NWP) model equations vary smoothly in space and time. Rainfall is not a directly predicted parameter from dynamical models, but is a diagnosed parameter from other model predicted parameters and appropriate physical parameterisation methods. Thus, the efficacy of the model also gets tested, basically by comparing the model predicted (inferred) rainfall and observed rainfall over land and oceans.

With the availability of many geostationary meteorological satellites around the globe since 1960s, including our own INSAT series from 1984, equipped with Very High Resolution Radiometer (VHRR) visible and infrared sensors, rainfall estimation (albeit indirectly) has improved significantly particularly over the oceans. Many orbiting satellites equipped with passive microwave sensors, are also providing precipitation estimates routinely, since 1980s, though at relatively poorer

* Corresponding author (E-mail: u.m.s.narayanan@gmail.com)

spatio - temporal resolutions over oceans and even over inaccessible land areas. The global precipitation products, based on measurements from satellite platforms, are freely available at many websites almost in near real time since the launch of Tropical Rainfall Monitoring Mission (TRMM) satellite in late 1997, which flew with the first active radar for direct observation of raindrops[1].

2 Materials and Methods

2.1 Rainfall measurements – Indian Efforts

India Meteorological Department (IMD) has a fairly good (and increasing) network of ground rain gauges since more than one and half centuries. Now many states, Karnataka in particular, have also their own dense rain gauge networks. The continuing growth of Automatic Weather Stations (AWS) and rain gauges around the country, maintained by a number of state government and private agencies, have enabled the consolidation of an excellent gridded daily rainfall data set (at 0.25° x 0.25° spatial scale) over the country from 1901 to date[2]. Fig. 1 shows the locations (in the elevation map of India) of the around ~ 6955 rainfall observation stations which go into making this gridded data set. The uncertainty in gridded products on station density, grid scale etc. have been discussed exhaustively[3,4].With the establishment of many (about 30) operational Doppler Weather Radars (DWR) around the coast and inland since 2000 by IMD, a new dimension for precipitation estimation (by remote sensing) has been made in India. Besides these, ISRO (Indian Space Research Organization), and some other Institutions also operate C, S, X - band radars in experimental mode in the country.

We have now regular rainfall measurements / estimates over the country from rain gauges (self - recording as well as tipping bucket), AWS, DWRs and Satellite platforms. Various attempts are on by many groups, mainly in ISRO and MoES (Ministry of Earth Sciences), to inter compare the measurements / products from satellites and other diverse sources, and even produce an integrated high resolution (both in time and space) rainfall product – on the same lines as GPM – IMERG[5,6].

Nine major International and National programmes have been conducted / participated by India since 1964, for studying various aspects of Indian Summer Monsoon (Appendix). The most important among them being the International Indian Ocean Experiment (IIOE 1964), monsoon experiment (MONEX 1979) and Indian Ocean Experiment (INDOEX 1999). The major

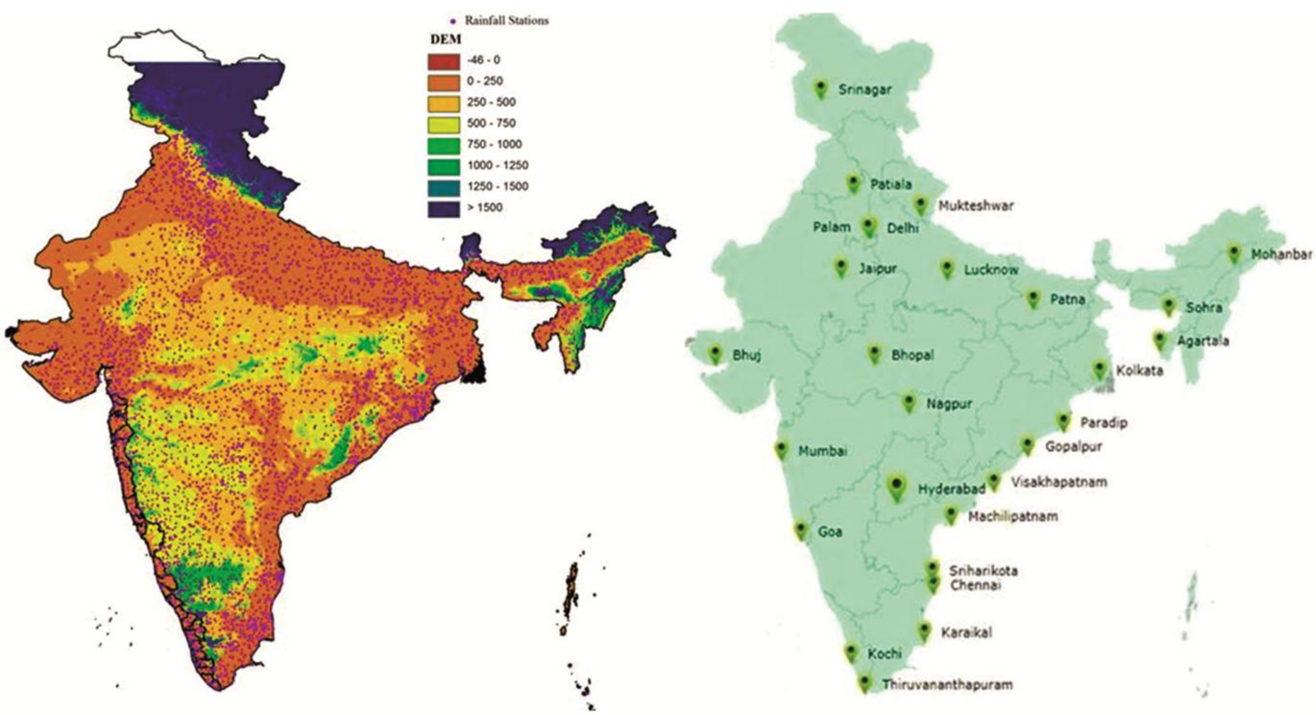

Fig. 1 — (a) Location of IMD rain gauges with elevation adopted from Thakur *et al.*[46] preparation of the gridded dataset, and (b) IMD – DWR network.

results from these programmes have been reviewed exhaustively by Krishnamurti[7], Collins *et al*.[8], Sikka[9] and Bhat and Narsimha[10].

However, none of these programmes has addressed the precipitation aspect – in an exclusive or exhaustive manner. Megha Tropiques satellite, a major Indo – French effort (which was a follow - on of MSMR on Indian Oceansat – 1 launched in 1999) and a part of Global Precipitation Mission (GPM), would have partly addressed this lacuna. But its rainfall measuring instrument, MADRAS (Microwave Analysis and Detection of Rain and Atmospheric Structure), with a five-frequency i. e. 18, 23, 36, 89 and 157 GHz (9 channel with both Horizontal (H) and Vertical (V) polarization except for the 23.8 GHz which had only the V polarization) passive microwave radiometer worked only for about one and half years (from Oct 2011 to Jan 2013)[11,12].However, the other microwave instrument on Megha-Tropiques, SAPHIR (Soundeur Atmospherique du Profil d'Humidite Intertropical par Radiometrie) for water vapour profiling operating at 183 GHz is still being utilised in rain estimation, both by GPM Precipitation Processing System (PPS) and by INSAT rain estimating algorithms[13]. For Megha Tropiques project, efforts were also made to establish a good validation site around Chennai [14].

The earliest attempts at quantitative precipitation estimates from satellites over Indian land and adjoining oceanic regions, can be traced to a small joint pilot experiment initiated by scientists of Space Applications Centre (SAC / ISRO), Indian Meteorological Department (IMD) and Space Science and Engineering Centre (SSEC), University of Wisconsin / USA, during MONEX / FGGE programme of 1979. Shifting of GOES (Geostationary Operational Environmental Satellite) (East), one of USA's two geostationary satellites, over Indian Ocean for an year during FGGE, was taken advantage of, by us. Simultaneous observations from visible and infrared hourly images from GOES - VHRR over three days of a northeast monsoon depression system during 12 – 14 November1979 and a newly established S - band radar (manually operated) at Cyclone Warning Centre, IMD, Chennai were collected. A new methodology[15], developed at Space Science and Engineering Centre (SSEC), was employed to estimate daily and 48 - hour accumulated rainfall from GOES (E), using SSEC's Man computer Interactive Data Access System (McIDAS). This collaborative work initiated in 1979, fructified under the Indo US Monsoon exchange programme. The GOES satellite and radar estimated rainfall were inter - compared with the available rain gauge observations[16]. An isolated study by Martin and Howland (1986) providing qualitative precipitation maps over the Arabian Sea exclusively from GOES (E) data was also conducted during this time[17].

The first successful Indian geostationary satellite, INSAT 1 – B with a VHRR instrument (with visible and infrared sensors), was launched in 1984. Daily Quantitative Precipitation Estimates (QPE) on 2.5° x 2.5° spatio - temporal grids, over the Indian land mass were made and compared with ground rain gauges[18] with reasonable success. INSAT – 1B was followed by launches of INSAT – 2D, INSAT - 3E and Kalpana VHRRs on geostationary satellite platforms for meteorological imaging, 2 – level wind determination, rainfall estimation, etc.

With the launch of Kalpana, INSAT 3E, INSAT - 3D and INSAT - 3DR in 2003, 2005, 2013 and 2016 respectively, which carried a 6 channel high resolution visible,mid infrared and thermal infrared sensors (VHRR), the estimation of precipitation (jointly by ISRO and IMD) are made operationally since 2010. INSAT 3D and INSAT 3DR also carried a 19 channel infrared sounder. All the above satellite payloads were designed and built at the Space Applications Centre (ISRO), as also the Oceansat-1 satellite. The rainfall products from INSAT (besides half hourly images, atmospheric winds, temperature –humidity profile, total ozone etc) are available in MOSDAC (Meteorological and Oceanographic Satellites Data Archival Centre) website of ISRO (https://www.mosdac.gov.in/) for registered users. The measured radiances from VHRR and from the 19 - channel temperature – humidity sounders of INSAT – 3D and 3 DR are also directly assimilated in weather prediction models[19].

Since ~ 2010, through advanced and improved algorithms, the rainfall products are being made available operationally from Kalpana (up to 2015), INSAT - 3D and INSAT - 3DR, at half-hourly and at 1° x 1°, as well as at 4 km x 4 km spatial grids. Gairola *et al*. (2014) have exhaustively reviewed the Kalpana derived rain rate products, both over land and oceans vis a vis TRMM, and IMD data[20,21].

In a major effort, India launched in 1999 the low orbiting sun synchronous, Oceansat – 1satellite, with a passive Multi - channel Scanning Microwave Radiometer (MSMR) (which was operated for two years) for estimation of precipitation and many other key atmospheric / oceanic parameters over global oceans (total perceptible and liquid water, ocean surface winds etc.), besides soil moisture over land, albeit at low spatial resolution of around 75 km x 75 km[22]. Microwave imager on Oceansat – 1 also carried a high resolution 8 - channel Ocean Colour Monitor (OCM) instrument operating in vis – near infrared spectral region (with 350 m resolution) for the study of biological aspects of ocean adjoining the Indian coasts[23].

2.2 Merged Precipitation Products

Tropical Rainfall Monitoring Mission (TRMM) and Global Precipitation Mission (GPM) became the buzz word by the end of last century in the context of rainfall estimates around the globe. Besides a 9 – channel [10.7 (H/V), 19.3(H/V), 21.3(V), 37.0(H/V), 85.5(H/V) in GHz] passive microwave radiometer, the TRMM satellite, launched in late 1997, was equipped also with an active radar operating at 13.8 GHz. The other instruments on TRMM were a 5 – channel (0.63, 1.6, 3.75, 10.8, and 12 μm) visible – infrared radiometer (VIRS), the Lightning Imaging Sensors and the Clouds and Earth's Radiant Energy System. Because of the active radar, TRMM got the distinction of being known as the first Rain Gauge in Space! The high temporal resolution, but indirectly estimated rainfall estimates from cloud tops by the IR sensors onboard the five Geostationary satellites around the globe, along with TRMM active and passive microwave instruments (and a few other microwave imaging sensors onboard orbiting meteorological satellites though with poorer spatio – temporal resolution, but with capability of directly sensing of raindrops), were combined judiciously to generate merged global rainfall products - TMPA (TRMM Multi satellite Precipitation Algorithm) - at 0.25° x 0.25° spatial and 3 - hourly temporalscales[1]. TRMM satellite, which was designed to work only for 3 years, was orbit - raised from 350 to 405 km after five years of launch, and this enabled it to function for a total of about 15 years (1998 – 2013) producing very valuable global precipitation data. Narayanan *et al*.[24] and Rahman *et al*.[25]reported the first comparisons of TMPA data over Indian land mass. Uma *et al* (2013) have shown that the TMPA data compare reasonably well with IMD daily gridded data at best only beyond 10° x 10° spatial scales[26]. They did a comparison between the two rain products on the seasonal scale for 9 years, and showed that the power of the 30 – 50 day and 10 – 20 oscillations match well. Prakash *et al* (2015) have evaluated the relative accuracy of various versions of TMPA products over India[27].Mitra *et al*.(2009, and 2013) have combined TMPA and IMD gridded rainfall data to produce improved merged products over Indian land mass and adjoining seas[5,28].

GPM (core) satellite was launched in 2014, with a13 – channel [(10 to 183 GHz), optimized 9 channel TMI frequencies along with 4 additional channels from 166 to 183 GHz to detect light precipitation and snowfall] and a Dual Precipitation Radar (DPR), operating at 13.6 and 35.5 GHz, to provide continuity of the TRMM service with better accuracy and more geographical coverage. Table 1 gives the comparative features of the two satellites.

The estimates of rainfall from the GPM microwave instruments, and from nine other orbiting satellites with microwave imagers (MeTOP- Meteorological Operational Satellite, NOAA- National Oceanic and Atmospheric Agency / Administration, SSMI- Special Sensing Microwave Imager) are used to estimate and calibrate the global rainfall products from infrared based (indirect) estimates from geostationary satellites. Many improvements (e.g. morphing technique) are continually taking place in the GPM rain estimation algorithms, as shown through various versions of the products[29.] These are now operationally available at 0.1° x 0.1° spatial grids and at 30 min time intervals from 2014 to date in real time and also in delayed mode as research products[1].

2.3 IMERG data

There are presently ten microwave imaging and sounding satellites in the GPM constellation, which are used to generate the high resolution IMERG data. These include AMSR2, GMI, ATMS, SSMIS-F16, SSMIS-F17, SSMIS-F18, MHS-MetOpA, MHS-MetOpB, MHS-NOAA18, and MHS-NOAA19[30]. Kidd *et al*. (2021) have exhaustively discussed various aspects of current and future requirements of global constellation of precipitation satellites[31]. Passive microwave data from these satellites are used

Table 1 — Rainfall related products over India available from different sources

Product	Spatial Resolution / Grid	Temporal Resolution
DWR (only reflectivity)	300 m x 300 m	10 min
IMD Gridded	0.25°x0.25°	Daily
Merged IMD – NCMRWF	0.25°x0.25°	Daily
INSAT – 3D / 3DR	4 km x 4 km& 1° x 1°	Half hourly
GPM / IMERG	0.1 x 0.1°	Half hourly

both directly and in morphed form, with infrared data starting to enter only when the time in question is more than about an hour away from a microwave overpass. IMERG achieves its half-hourly spatial resolution following the Kalman Filter morphing approach. The IR weight fields (obtained a priori tells for each grid box and for each time how much the IR is weighted in.DPR data of GPM Core) are not used directly, but only as part of the combined product and as a calibrator[32].

IMERG level 3 final product integrates algorithms from TMPA, CMORPH, and PERSIANN to produce high resolution rainfall estimates. Details of the morphing and estimation of final IMERG is well described in various articles[33,34]

Surface radar products are not used in IMERG computation due to their sparseness around the globe, although one could do that on a regional basis wherever they exist. IMERG global data have become very popular in the scientific and social community. The reasons being: IMERG system utilizes besides GPM (core), all other microwave imaging and microwave water vapour sounding satellite instruments around the globe. GPM's higher frequency (153 – 182 GHz) channels enable better estimation of light rain and snow. Its DPR is able to calibrate the microwave observations much better.

It is clear those correlations between full-resolution IMERG (or other satellite) products and surface rainfall data are presently modest at best. Spatio – temporal averaging improves the picture as the large random error of the original retrievals tends to cancel out with increasing level of averaging.

Presently, Version 5/6 of the IMERG data are available in public domain. For their use in regular / operational scenario, these products are being validated continually by many groups for different regions of the globe, as also in India by various groups for scientific and various applications[27,35,36]. Version 7 with improved morphing to largely ameliorate the smoothing is likely to be available shortly (Huffman G J, NASA (National Aeronautics and Space Administration) /GSFC, Peronal Communication).

2.4 Indian Doppler Weather Radars (DWR)

The DWR reflectivity (proxy for rain rate) images at 10 minute intervals are available at IMD website. However, the rain rate products over about 150 km circular area around the DWR site are generated only on special occasions or on specific demand by the user. The radial wind data are regularly available and are also assimilated in IMD/NCMRWF models[37]. The rainfall - radar reflectivity (Z – R) relationship needs to be established exclusively for each DWR instrument, location, season, type of rainfall etc, For a few DWRs, this effort has been done by Suresh *et al*.[38], Subrahmanyam and Baby (2020)[39].Efforts are also being made to assimilate DWR reflectivity data in regional models by NCMRWF /IMD in an experimental mode[40].

However, it is necessary and important to have a feel of the actual rainfall products from various DWRs in relation to the IMD gridded rainfall data / rain gauge observations and from INSAT, IMERG etc. All the users (including modelers) want actual rainfall products per seat various spatio temporal resolutions. In view of the increasing extreme rainfall events (ascribed to Climate Change)[41] high spatio – temporal resolution surface rain rate data have become very relevant. Their efficacy for various process studies can be judged only through the use of the actual rainfall products from radar reflectivity. Many isolated case studies have been carried out using the rainfall retrieved from some of these radars (as also some C, S and X band radars) using the Z – R relationship established by the concerned scientists or as provided by the manufacturer[39,42].

3 Results and Discussion

3.1 Case study with Chennai DWR

A case study during a very intense and sustained rainfall event of Nov - Dec 2015 over Chennai was carried out by us[43], to inter compare the rainfall derived from four different data sources. Two long - lasting heavy rainfall events, associated with low pressure systems occurred over Chennai and adjoining areas on 14 – 15 Nov 2015 and on 30 Nov – 01 Dec 2015. On 15 Nov 2015, a well-marked low-pressure area moved northwards along the Tamil Nadu coast, resulting in huge amounts of rainfall over coastal Tamil Nadu and Andhra Pradesh with 24-hour totals amounting to ~ 300 mm over most of Chennai and suburbs.

On 28-29 November, another system developed and arrived over Tamil Nadu on 30 November, bringing additional rain and flooding. The system produced around 400 mm of rainfall in 24 hours ending 1 December, 2015 over most of Chennai.

The rains lasted for more than 24 hours without any interruption during both the events, varying in intensity over the day and at different locations under the DWR coverage. This provided an excellent opportunity to inter compare the large scale features of rainfall from four different platforms at various spatio-temporal scales.

i) Chennai DWR – SRI (surface rainfall intensity) at 10 minute intervals and PAC (precipitation accumulation over 24 hr) data both at ~ 300 m spatial scale,

ii) (a) GPM – IMERG data at 0.1° x 0.1° spatial and half hourly time scale and
 (b) GPM – GMI (GPM Microwave Imager) data at 4 km x 4 km resolution at instantaneous time scale

iii) INSAT 3D rainfall by Hydro Estimator (HE) method and INSAT multispectral Rainfall Algorithm (IMSRA) methods at half hourly time scale and at 4 km x 4 km and 1° x 1° spatial scale respectively

iv) IMD daily gridded rainfall at 0.25° x 0.25°.

All the products were brought to a common space – time grid (e.g. 0.1°, 0.2° and 30 min) for the inter comparison. The 300 m spatial resolution DWR data were rescaled to 4 km, 0.1° and 1° in the spatial domain. The 10 min DWR rain data were up scaled to half hour (by adding two adjacent observation times) and also to 24 hour cumulative scale by adding all the 10 min samples of the day (144 values). For comparison with GPM microwave imager products (at 4 km resolution and at the satellite over pass time), we used the nearest 10 minute DWR observation. For comparison with IMERG and INSAT products (available at 30 min intervals), three consecutive 10 min DWR observations were clubbed. Daily rainfall values were compared for three datasets using the 1° x 1° area for GPM – IMERG and INSAT – 3D HE products with DWR. We also compared the various products at larger spatial and time scale (by making daily DWR rain products, adding up all the observations of 24 hours). It is presumed that at higher spatio - temporal scales, the match would be better.

Large discrepancies with IMD gridded data both in DWR and satellite products are clearly observed (Fig. 2) even on accumulated daily scale. This shows the need for a more systematic study to generate and validate the rain products from all remote sensing sources/analysis with in situ observations. Initial comparison has shown varying correspondence between the instrumental estimates: correlation coefficient (cc) of DWR with GPM – IMERG being ~ 0.4 for 15 Nov and ~ 0.8 for 01 Dec case, but only ~ 0.3 to 0.6 with INSAT – 3D (Fig. 2). With IMD gridded product, the correlation shows ~ 0.6 for 15 Nov and 0.8 for 01 Dec case. It can be noticed that cc values for GPM - IMERG are having better match with IMD4 data.

In general, GPM is observed to be over estimating and INSAT-3D is underestimating the rainfall as compared to the DWR values. The values of rainfall are in the decreasing order as IMERG, INSAT and DWR.DWR data (~ 300 m and continuous) provides a good measure for comparison. Improved correlation coefficient between DWR and GPM is observed on larger spatial scale.

Radar – rain gauge data merging methods for hydrological applications has been discussed by Rodriguez *et al.*[44]. It is also important to merge in this approach the satellite precipitation estimates.

We are suggesting a two step approach for merging satellite, DWR and IMD products:

- First establishing a Z – R relation for individual DWR with IMERG at high spatio – temporal resolution. This can be done over the coastal oceans also, besides over land.
- Then comparing the DWR daily rainfall with IMD4 gridded products. DWR rainfall can then be taken to revalidate the satellite estimates

In view of the sparse network of ground rain gauges for establishing a sound Z – R relationship for each DWR in the conventional way, it may also be attempted to establish a statistically significant Z – IMERG rainfall relationship at half hourly time scale. This can then be updated every few months with the help of IMD monthly gridded rainfall data / available recording rain gauges, till a stable relationship is established for each radar.

3.2 Major Inferences

Since MONEX – 1979, we have come a long way, with significant improvements in our infrastructure in atmospheric measurements of all important parameters from a variety of platforms, with an excellent ground truth. Dynamical Model forecasts from various types of models (global as well as regional), are also carried out at many Institutions.

Many case studies have been presented to validate INSAT and the merged products (TMPA from TRMM, IMERG from GPM) by many Indian groups[6,20,36]. Qualitative comparisons involving case studies have yielded somewhat better results. However, the reliability of even daily (24 hour accumulated) quantitative rainfall estimates from satellites, are able to be taken with some confidence only on all India spatial scale[36,45]. Figure 3(a) shows the day-to-day time series comparison of 122 monsoon days during 2016 monsoon from various satellite products with IMD gridded accumulated rainfall, over whole of Indian land mass. At best the peaks and valleys, between IMERG and IMD data match.

Figure 3(b), shows a similar comparison of mean rainfall data of four years (2014 – 2017) of the two data sets. From 18 years seasonal all India mean of TMPA / IMERG and IMD gridded rainfall data, Thakur (2020) has seen the two products to be having a mean bias of around 150 mm, which is significantly more than the standard deviation of the inter-annual variability of monsoon (~ 90 mm i.e. 10%)[46]. Due to

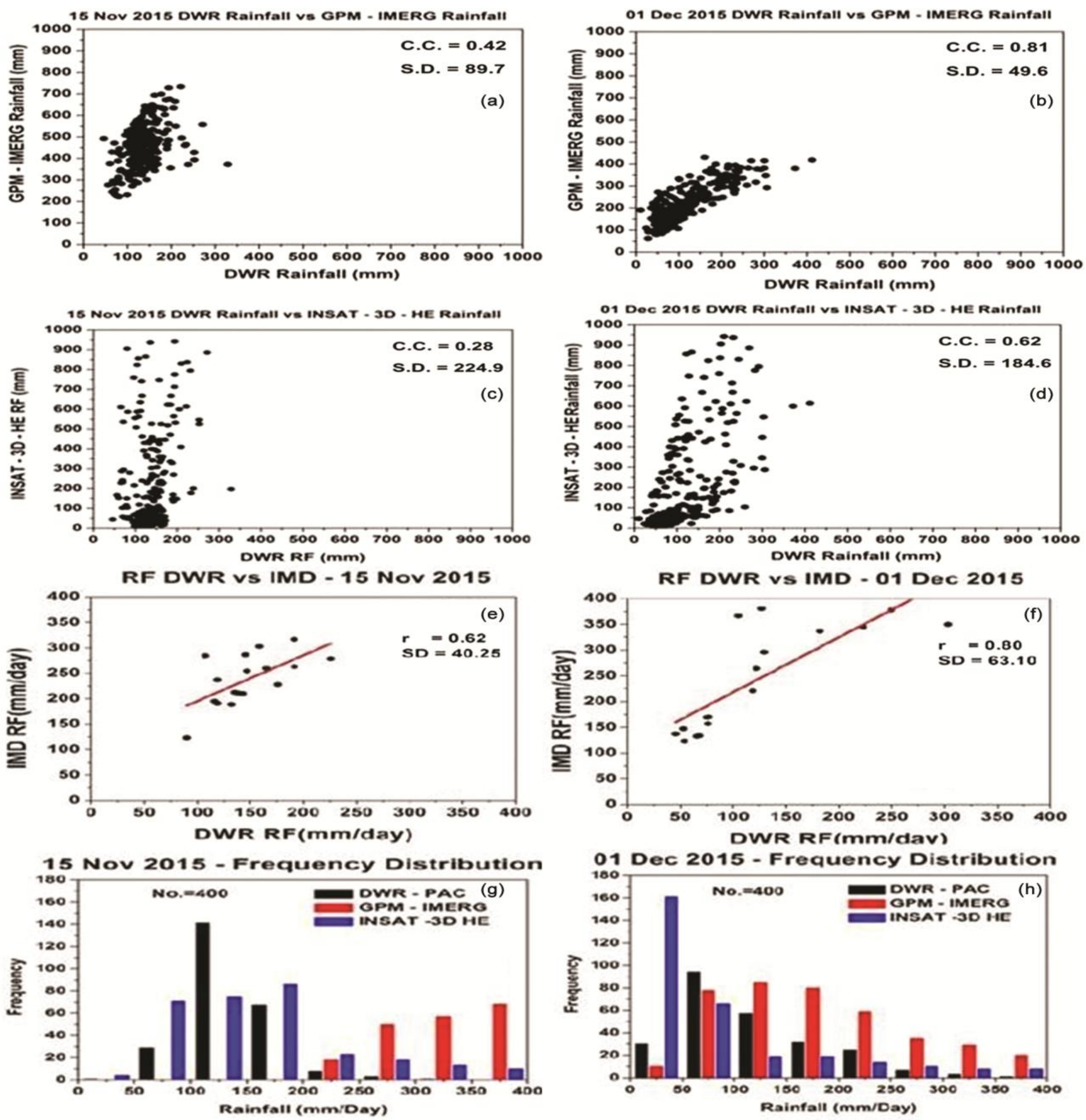

Fig. 2 — Chennai deluge, 14-15 November and 1, 2 December, 2015. Intercomparison of rainfall estimates from Chennai DWR, IMD gridded data, IMERG, and INSAT-3D[43].

the high spatial and temporal variability of precipitation, the validation of satellite estimation (both from INSAT and merged GPM) requires special and continuous efforts to achieve better compatibility with the IMD4 gridded data[47]. At best, only on all India scale, daily 24 hour accumulated rainfall values can be acceptable to be quantitatively comparable with IMD gridded data.

The precipitation products (and their spatio-temporal scales) available in public domain from INSAT products in MOSDAC), MoES (gridded daily rainfall, DWR products), IMERG products from GPM are summarised in Table 2.

In short, though IMERG satellite products are available at a very high spatio - temporal scale, their usability is severely limited over the Indian land mass where highly reliable ground truth data are available (but only on daily scale) for a long period of time. On the other hand DWR rain products are available only on special request. Operationally, in public domain only DWR reflectivity maps are available. Combining the two products (of DWR and IMERG) appropriately will be the proper approach to get continuous rainfall with high spatio – temporal resolution over Indian land mass and over coastal oceans.

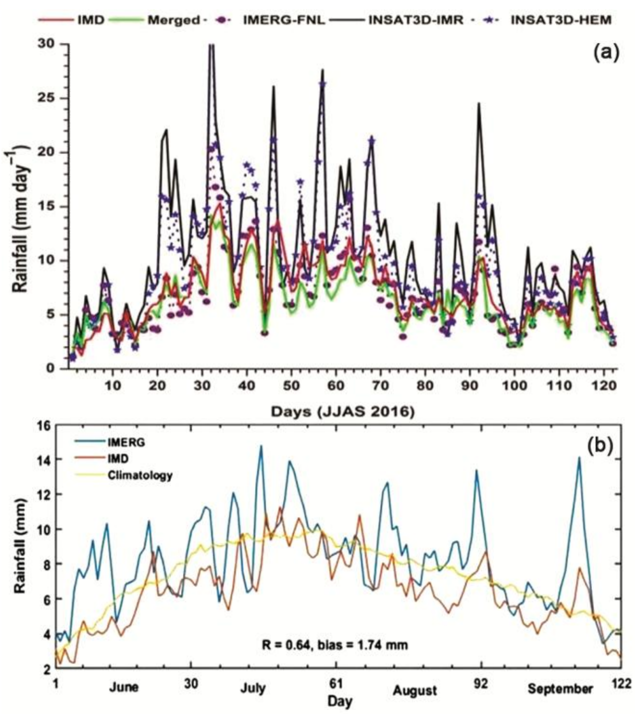

Fig. 3 — (a) Daily all India rainfall of 2016 from IMERG (version 4), INSAT-3D and IMD gridded data sets[46], and (b) Daily all India mean Rainfall of 4 years (2014-2017) from IMERG (version 5), and IMD gridded data sets[46].

3.3 Development of Validation sites - Understanding the sub-pixel and sub-sample variability of rainfall.

Satellite-based rainfall estimates typically represent larger space and timescales. A main difficulty in this regard is that remotely sensed rainfall estimates are provided in spatially averaged pixels (typically 1-4 km^2) and no equivalent ground reference data are usually available because of the sparseness of rain-gauge networks[48]. Super-dense network of rain gauges have been installed (dense network of approximately 200-400 automated rain gauge stations within 20 km x 20 km area),in various developed countries to explore in detail the uncertainties and errors caused by rainfall variability at remote-sensing sub-pixel resolution. This network will also be helpful in understanding the uncertainties in satellite-derived rainfall estimations due to sub pixel scale processes. Such a site can be established around the range of a coastal DWR station.

A modest attempt of establishing a network of 24 automatic rain-gauges was made during Megha Tropiques project for validation of satellite data around Gadanki / Chennai[14].

4 Conclusion

In the light of the above developments, existing / being established infrastructure, it is important that India embarks upon a well-coordinated programme to bring the various precipitation measurements / products to a common grid, validate them and establish unambiguously the spatio - temporal scales at which

Table 2 — Overview of TRMM and GPM observatories

Feature	TRMM	GPM
Microwave Imager	TMI: 9 channels (H/V)[10.7 (H/V), 19.3(H/V), 21.3(V), 37.0(H/V), 85.5(H/V) in GHz]	GMI: 13 channels (H/V) (10 to 183 GHz), optimized TMI + 4 channel from 166 to 183 GHz
Active Radar	PR: Ku band 13.8 GHz	DPR : Ka and Ku band 35.6 and 13.5GHz
VIRS	5 channels (0.63, 1.6, 3.75, 10.8, and 12 μm)	5 channels (0.63, 1.6, 3.75, 10.8, and 12 μm)
Inclination	35 ° - 40 °	60°
Height	350- 402.5 Km	407 Km
MI Swath	878 Km	885 Km

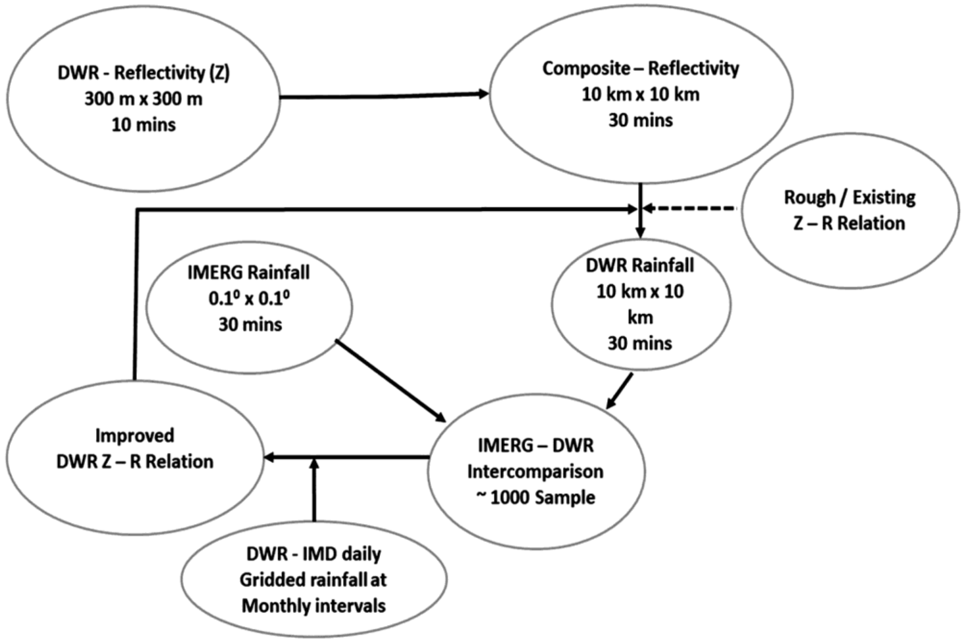

Fig. 4 — Block diagram for establishing / improving Z – R relation of DWR from IMERG data.

they are reliable over different zones of the country.

An effort towards the above, for a full monsoon season (covering both monsoons) is needed to put the precipitation measurements with desired level of confidence. The level of accuracy needed from the perspective of the need for the next 5 – 10 years, from satellites vis a vis IMD grid data can be roughly summarised below.

These are the technical / scientific issues to be addressed.

a) At all India seasonal scale, satellite products should be within 5 % of the all India cumulative IMD gridded product. At its own relative scale, the Inter-annual Variations (IAV) of ISMR should be able to be picked from IMERG data. Today the IAV many a times gets submerged in the errors of measurement of satellite data

b) At the daily all India scale the accuracy should be at least within 10% of IMD product, so that the relatively high and low rainfall phases are well distinguished. At the homogeneous spatial scales, these could be within ~ 15% of IMD gridded data. Similar effort over adjoining ocean may have to be examined. This is important also in the context of expected precipitation pattern changes in the impending Climate Change scenario[41].

With the ultimate aim of making combined rain products reasonably compatible with ground truth at least at 2° x 2° and three hourly time scales – the following method may be adopted.

- Examine systematically from the start of the 22 years of GPM era, at what time scale, the present satellite merged products are comparable with ground data at spatial scales of 2° x 2°, 5° x 5°, all India scale etc. And similarly at what spatial scale, satellite products are reliable at time scales of 1 hour, 3 hours, 24 hours, etc.
- Assess the applicability of spatio – temporal gradients of rainfall from one time / place to another for each data source. In absence of achieving very high absolute accuracies, relying on gradients may be a good option to begin with.
- Prepare rainfall products from all sources, e. g. satellite, DWR, rain gauge etc compatible on a common grid (say at 0.25° x 0.25°, 3 hourly and daily all India), besides the grids that each group is making presently.
- Make rainfall products operationally at a standard spatio - temporal scale from all possible DWRs in the country. For this Z – R relations for each radar is needed. As a first step, rough Z – R relationship can be derived for each radar using the reflectivity values and the closest half hourly GPM IMERG rain rate (at 0.1° x 0.1° spatial scales). This relation can be constantly improved from time to time with more and more Z (from DWR) and R

(from IMERG) values. On monthly time intervals, the above relation can be further refined using the IMD gridded data. Figure 4 shows a block diagram suggesting the procedure for carrying out the same.

- Study accuracy of INSAT based estimates vis a vis microwave observations on all India scale on a regular basis
- Accuracies obtainable for convective and stratiform rainfall.

As a prelude to this, a Pilot study over a smaller area (say Monsoon core region and Chennai DWR region – where a cluster of rain gauges exist) for a month may be organised to understand the likely intricacies of a major full year Monsoon Precipitation Programme.

The above effort will also help India consolidate in designing and launching an appropriate Indian Rain mapping (passive microwave + Radar) orbiting satellite, as a complement to INSAT. This will be our contribution to GPM project and to further improve the rainfall products over India and tropical oceans.

Appendix — National / International Experiments conducted on Monsoon

Programs conducted on Monsoon	Abbreviation	Year of conduct
International Indian Ocean Experiment	IIOE	1964-67
Indian Summer Monsoon Experiment	ISMEX	1973
Indo Soviet Monsoon Experiment	Monsoon-77	1977
Monsoon Experiment	MONEX	1979
Monsoon Trough Boundary Layer Experiment	MONTBLEX	1990
Land Surface Processes Experiment	LASPEX	1997-98
Joint Air Sea Interaction Experiment	JASMINE	1999
Indian Ocean Experiment	INDOEX	1999
Arabian sea Monsoon Experiment	ARMEX	2002-05

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