Validation of INSAT-3D derived rainfall estimates (HE & IMSRA), GPM (IMERG) and GLDAS 2.1 model rainfall product with IMD gridded rainfall & NMSG data over IMD's meteorological sub-divisions during monsoon

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सार – भारतीय ग्रीष्म मॉनसून ऋतु (जून, जुलाई, अगस्त, सितम्बर) के दौरान होने वाली वर्षा का भारतीय अर्थव्यवस्था में महत्वपूर्ण स्थान है। दक्षिणी-पश्चिमी मॉनसून के दौरान सामान्य या सामान्य से अधिक वर्षा का होना देश के सकल घरेलू उत्पाद (GDP) में कृषि की हिस्सेदारी में वृद्धि को दर्शाता है। 82° पूर्व में स्थित इनसैट - 3डी मौसम विज्ञान को समर्पित एक भू-स्थिर उपग्रह है जिसे 26 जुलाई, 2013 को प्रक्षेपित किया गया। वर्तमान समय में इनसैट - 3डी से वर्षा आकलित करने वाले तीन उत्पाद तैयार किए जा रहे हैं जिनके नाम है:- मात्रात्मक वर्षा अनुमान (QPF), इनसैट मल्टी स्पेक्ट्रल वर्षा एल्गोरिथ्म (IMSRA) और हाइड्रो अनुमानक (HE)। इस शोध पत्र में ग्लोबल लैंड डेटा एसीमीलेशन सिस्टम (GLDAS2.1) के नोह मॉडल (Noah Model) पर आधारित वर्षा उत्पादों का उपयोग किया गया है। नोह एक 1-डी कॉलम मॉडल है जो युग्मित अथवा अयुग्मित किसी भी मोड में क्रियान्वित किया जा सकता है। इस अध्ययन में वर्ष 2015 के मॉनसून ऋतु के लिए भारत मौसम विज्ञान विभाग के वर्षा-ग्रिडेड डेटा और वर्ष 2016 के मॉनसून ऋतु के लिए IMD और NCMRWF द्वारा 0.25° × 0.25° ग्रीड पर तैयार किए गए NMSG वर्षा आँकड़ों का उपयोग भारतीय भूभाग में 2015 एवं 2016 के दक्षिणी-पश्चिमी मॉनसून ऋतु (JJAS) के दौरान HE, IMSRA, GPM (IMERGE) और GLDAS2.1 नोह वर्षा उत्पादों (0.25° × 0.25° रिजोल्यूशन डेटा) को वैधीकृत करने के लिए संदर्भ डेटा के रूप में इस्तेमाल किया गया है। यह वैधीकरण वर्ष 2015 एवं 2016 के मॉनसून ऋतु के 10 कि.मी. के स्थानिक रिजॉल्यूशन और मासिक अल्पकालिक (Temporal) रिजॉल्यूशन के स्तर पर किया गया है।

भारतीय क्षेत्र के ऊपर वर्ष 2015 के मॉनसून ऋतु के दौरान GLDAS2.1 से प्राप्त वर्षा उत्पाद के सहसंबंध गुणांक और RMSE मानों का आई एम डी के वर्षा ग्रिडेड डेटासेट के साथ वैधीकृत किया गया जो क्रमश: 0.83 और 100.05 मि.मी. पाया गया है। उपग्रह से प्राप्त किए गए अनुमानित वर्षा उत्पादों जैसे: HE, IMSRA और GPM (IMERG) में से HE ने भारतीय क्षेत्र के ऊपर सबसे अच्छा मिलान दर्शाया है जिसके सहसंबंध गुणांक और RMSE के मान आई एम डी के वर्षा ग्रिडेड डेटासेट के साथ यही मेल खाते हैं जो क्रमश: 0.72 और 160.94 मि.मी.पाए गए हैं।

भारतीय क्षेत्र के ऊपर वर्ष 2016 के मॉनसून के दौरान GLDAS2.1 से प्राप्त वर्षा उत्पाद के सहसंबंध गुणांक और RMSE मानों का NMSG के डेटासेट के साथ मिलान करने पर क्रमश: 0.87 और 105.13 मि.मी. पाया गया जो वैधीकरण में प्रयुक्त सभी वर्षा उत्पादों में सबसे अच्छे मेल को दर्शाता है। उपग्रह से प्राप्त किए गए अनुमानित वर्षा उत्पादों जैसे: HE और IMSRA में से HE ने भारतीय क्षेत्र के ऊपर सबसे अच्छा मिलान दर्शाया है जिसके सहसंबंध गुणांक और RMSE के मान आई एम डी के वर्षा ग्रिडेड डेटासेट के साथ सही मेल खाते हैं जो क्रमश: 0.81 और 179.52 मि.मी. पाए गए हैं।

ABSTRACT. Rainfall during Indian Summer Monsoon (JJAS) is an important factor of Indian economy. A normal to above normal rainfall during southwest (SW) monsoon results in increase in the share of agriculture in country's GDP. INSAT-3D is a geostationary dedicated meteorological satellite launched on 26th July, 2013, located at 82° E. At present three rain estimate products are being generated from INSAT-3D namely; Quantitative Precipitation Estimate (QPE), INSAT Multispectral Rainfall Algorithm (IMSRA) and Hydro Estimator (HE). Rainfall product of Global Land Data Assimilation System (GLDAS 2.1) based on Noah Model is used in this study. Noah is a stand-alone, 1-D column model which can be executed in either coupled or uncoupled mode. In this study, IMD rainfall gridded data

for the monsoon season 2015 and NMSG rainfall data at a 0.25° × 0.25° grid generated by IMD & NCMRWF for the monsoon season 2016, are used as the reference data for validating HE, IMSRA, GPM (IMERGE) and GLDAS2.1 Noah Rainfall products (0.25° × 0.25° resolution data) during SW monsoon season (JJAS) 2015 & 2016 over Indian region. The validation is done at10 km spatial resolution and monthly temporal resolution of monsoon sessions 2015 & 2016.

The value of correlation coefficient and RMSE of Rainfall product from GLDAS2.1 validated with IMD rainfall gridded dataset are 0.83 & 100.05 mm respectively over India region during 2015 monsoon season which is a best fit among all rainfall products used in validation. Among satellite derived rainfall estimate products: HE, IMSRA & GPM (IMERG); HE shows best fit correlation coefficient and RMSE with IMD rainfall gridded dataset, *i.e.*, 0.72 & 160.94 mm respectively over Indian region.

The value of correlation coefficient and RMSE of Rainfall product from GLDAS2.1 validated with NMSG are 0.87 and 105.13 mm respectively over India region during 2016 monsoon season which is a best fit among all rainfall products used in validation. Among satellite derived rainfall estimate products: HE&IMSRA; HE shows best fit correlation coefficient and RMSE with IMD rainfall gridded dataset, *i.e.*, 0.81 & 179.52 mm respectively over Indian region.

Key words – IMD rainfall gridded dataset, GLDAS 2.1, HE, IMSRA, GPM (IMERGE).

1.   Introduction

India is an agricultural country; the SW monsoon season (JJAS) is the main rainfall season for almost whole country [except Tamil Nadu which gets rain during NE monsoon season (OND)]. The success and failure of crops in large region of country depend on the rainfall during SW monsoon season as it brings over 60-80% of India's annual rainfall (Prakash *et al.*, 2014). India is the seventh largest country in terms of area in the world therefore it is very difficult to maintain a network of manual meteorological observatories. Moreover, the numbers of extreme events such as extremely heavy downpours, cloud bursts, floods etc. have increased in near past and as per the views of experts they will increase in future due to global climate change. Therefore, it is need of the hour to have proper and accurate knowledge of the spatial and temporal distribution of rainfall at finer resolutions. To prepare for the present and future needs, India Meteorological Department has established a network of manual observatories, automatic weather stations, automatic rain gauges, ground based radar network. But it is a fact that the rain gauges and radar network is not well distributed over whole Indian region and the coast of establishing a well distributed network is very large; So an alternative is required which can provide rain estimates all over Indian region at a defined spatial and temporal resolution. This task can be easily accomplished by using meteorological satellites both in geostationary orbit for Indian region and polar orbit for global. Hydrologists all around world have developed various algorithms to get rainfall estimates from the meteorological satellites (Arkin and Meisner., 1987; Adler *et al.*, 1993 and 2000; Todd *et al.*, 2001; Haile *et al.*, 2010; Joyce *et al.*, 2004). India has deployed three meteorological satellites namely Kalpana1, INSAT-3A & INSAT-3D in geostationary orbit. Algorithms are developed for the estimation of rainfall by these Indian satellites (Kumar and Varma, 2017) which provide rain estimates at a temporal resolution of half-hourly, daily, monthly and seasonal.

Thermal infrared (TIR) band (10.8 μm) data is widely used in rainfall estimations, as it provides information about the cloud top brightness temperature (CTBT). CTBT is used because it is assumed that clouds with a colder CTBT produce heavier rainfall (Haile *et al.*, 2010), but as the TIR measurements do not penetrate the clouds and have a weak relation with rainfall rates. Moreover, with TIR based measurements another drawback is the rainfall area detection (Ba and Gruber, 2001). Because of this drawback the rainfall pixel is not properly delineated which in turns leads to either over or underestimation of rainfall area or in some cases oversight of a complete rainfall event. Therefore, identification of rainy pixel is the most important task for estimation of rainfall using TIR band. All over world many indices are developed for the detection of rainfall area that utilize CTBT, *i.e.*, TIR band along with multispectral data like Visible band, WV-band, other IR-bands sensors present on various advanced geostationary satellites presently orbiting the Earth.

Since the deployment of meteorological geostationary satellites various algorithms are developed around the world. Arkin and Meisner (1987) had given a simple thresholding technique to screen raining and non-raining pixels. They used TIR channel and defined a CTBT threshold of 235 k, if the pixel has CTBT below 235 k then it is considered as a raining pixel otherwise it is be neglected as non-raining pixel (Arkin *et al.*, 1989; Bhandari and Varma, 1995). Many rainfall estimation algorithms follow this approach (Haile *et al.*, 2010; Huffman *et al.*, 2007; Todd *et al.*, 2001). But with this approach there is a drawback that it cannot identify thin cirrus clouds, which usually have a low CTBT but do not produce rainfall, nor can it identify rain falling from warm clouds and orographic rain. Many have identified this drawback and literature is available stating the same like Vicente *et al.* (1998) has mentioned that using only CTBT for rainfall area detection without considering the evolution of the cloud system will result in overestimation as well as under estimation of rainfall over area as a result

of excessive area of precipitation. To overcome this effect, they recommended to additionally considering a cloud growth rate correction factor to improve the detection of rain pixels. It has been shown that the relationship between CTBT and rain rate is not consistent and varies regionally (Todd *et al.*, 2001). Various threshold values are developed and used for different regions in different algorithms (Ba and Gruber 2001; Todd *et al.*, 2001; Roca *et al.*, 2002; Kalinga and Gan, 2010). Moreover, with advanced geostationary satellites other indices like brightness temperature difference (BTD) at TIR-WV band (10.8-6.2 μm) and TIR1-TIR2 (10.8-12.0 μm) channels are being used for rain area detection (Ba and Gruber 2001; Haile *et al.*, 2010; Mishra *et al.*, 2009; Thies *et al.*, 2008; Kuhnlein *et al.*, 2014; Behrangi *et al.*, 2009).

In this study, we have validated INSAT-3D rain estimates with NMSG data. INSAT-3D is a dedicated meteorological satellite of INSAT series (INSAT or the Indian National Satellite System is a series of multipurpose Geo-stationary satellites launched by ISRO to provide meteorological services. Commissioned in 1983, INSAT is the largest domestic communication system in the Asia Pacific Region) designed for enhanced meteorological observation and monitoring of land and ocean surfaces of weather forecasting and disaster warning. INSAT-3D is located in geostationary orbit, altitude of ~35, 786 km, location at 82° E. INSAT-3D has four payloads, two meteorological payloads namely: Six channel Imager, Nineteen channels IR Sounder, One Data Relay Transponder and One Satellite Aided Search and Rescue (Table 1). The INSAT-3D imager provides imaging capability of the earth disc from geostationary altitude in one visible (0.52 - 0.72 micrometers) and five infrareds; 1.55 - 1.70 (SWIR), 3.80 - 4.00 (MIR), 6.50 - 7.00 (water vapour), 10.2 - 11.2 (TIR-1) and 11.5 - 12.5 (TIR-2) bands. The ground resolution at the sub-satellite point is nominally 1 km × 1 km for visible and SWIR bands, 4 km × 4 km for one MIR and both TIR bands and 8 km × 8 km for WV band (Table 1).

2. Data used

In this study IMD rainfall gridded data of monsoon 2015 season and NMSG data of monsoon 2016 season are used as reference for validating INSAT-3D rain estimate products (HE & IMSRA), GPM (IMERG) real time dataset (for 2015 only) and GLDAS2.1 rainfall dataset.

2.1. *NCMRWF Merged Satellite Gauge (GPM) data (NMSG)*

This dataset is outcome of joint work of IMD and NCMRWF (Mitra *et al.*, 2009). The dataset is available

TABLE 1

Channel specifications of INSAT-3D Imager Payload

Channels number	Channel ID	Channel name	Spectral range (μm)	Resolution (km)
1.	VIS	Visible	0.55 - 0.75	1.0
2.	SWIR	Short Wave Infrared	1.55 - 1.70	1.0
3.	MIR	Medium Wave Infrared	3.7 - 3.9	4.0
4.	WV	Water Vapour	6.5 - 7.1	8.0
5.	TIR1	Long Wave Infrared	10.3 - 11.3	4.0
6.	TIR2	Split	11.5 - 12.5	4.0

on IMD, Pune website (http://imdpune.gov.in/Seasons/ Temperature/gpm/). The dataset is at 0.25° spatial resolution and daily temporal resolution. This National Centre for Medium Range Weather Forecasting (NCMRWF) Merged Satellite Gauge (NMSG) algorithm uses first guess rainfall information obtained from GPM satellite estimates over land and Ocean (Mitra *et al.*, 2009) by using successive correction method.

2.2. *HE - Hydro estimator*

Hydro-estimator provides pixel-scale, half-hourly precipitation rate measurements over land and oceans. INSAT-3D Imager observations in TIR1, TIR2 and WV channels combined with Numerical Weather Prediction (NWP) forecasts are used to estimate high spatial-temporal resolution rainfall estimates. The H-E uses an algorithm based on IR cloud top temperatures, temperature changes and gradients to produce rainfall rate estimates along with NCEP/GFS parameters and earth elevation model on half hourly basis. The various corrections and adjustments are applied to the estimates product such as parallax correction (satellite viewing angle), available moisture (derived from the model) and orographic correction. Thermodynamic model is used for calculating EL / LNB correction for warm rain. Orographic correction is carried out using wind and elevation model. Dry atmospheric correction is carried out using RH. Rain is determined at each pixel using different relationships for convective/ strati form type of cloud and relationship dynamically calculated for each pixel. The spatial resolution of product is Pixel level (4 km at nadir) and temporal resolution is half-hourly. The product dimension is 81° S - 81° N and 3° - 163° E, but for this study daily accumulated rainfall estimate over Indian region is used for calculating monthly accumulated rainfall from IMDPS, New Delhi. The description of HE algorithm can also found elsewhere

in (Kumar and Varma, 2017). The algorithm had undergone major revision in 2015 in order to improve the orographic precipitation and modified algorithm was made operational from mid-August, 2015 (Varma *et al.*, 2015).

2.3. *IMSRA - INSAT multispectral rainfall algorithm*

IMSRA combines variety of techniques (IR and MW) in a single and comprehensive rainfall algorithm. The QPE products are derived using TIR1 and WV channels brightness temperature from INSAT-3D imager. The observations in IR and WV bands are utilized to classify clouds into several categories, such as low-level clouds, thin cirrus, convective and deep convective clouds, etc. (Roca *et al.*, 2002). The most important aspect of this scheme is that it allows delineation of cirrus clouds, which is one of the major sources of error (Barret and Martin, 1981) in IR-based rain algorithms and helps identify convective and deep convective rain clouds. The product spatial resolution is $0.1° \times 0.1°$ and temporal resolution is half-hourly. The product dimension is 30º E to 120º E and 40º S to 40º N, but for this study daily accumulated rainfall estimate over Indian region is used for calculating monthly accumulated rainfall from IMDPS, New Delhi. The spatial interpolation method applied in box averaging.

2.4. *GLDAS2.1 Noah LSM - Rainfall product (GNMRP hence forth)*

The Global Land Data Assimilation System (GLDAS) is to ingest satellite and ground based observational data products, using advance surface modeling and data assimilation techniques, in order to generate optimal fields of land surface states and fluxes (Rodell *et al.*, 2004). GLDAS drives multiple, offline land surface models, integrates a huge quantity of observation based data and executes globally at high resolution (2.5 to 1 km), enabled by the Land Information System (LIS) (Kumar *et al.*, 2006). At present, GLDAS drives four land surface models (LSM): Noah, Catchment, the Community Land Model (CLM) and the Variable Infiltration Capacity (VIC). GLDAS-2 has two components: one forced entirely with the Princeton meteorological forcing data (GLDAS-2.0) and the other forced with a combination of model and observation based forcing datasets (GLDAS-2.1). For this study, we have used Noah LSM based GLDAS2.1 data at 0.25° resolution. The temporal resolution of reanalysis GLDAS-2 products is 3-hourly. Monthly products are generated through temporal averaging of the 3-hourly products and downloaded via https://earthdata.nasa.gov/.

2.5. *GPM (IMERG)*

The Global Precipitation Measurement (GPM) mission core satellite was launched in February 2014 with the goal of providing the next-generation, state-of-the-art global quantitative precipitation estimates (QPE). Taking advantage of an international constellation of satellites of opportunity, the Integrated Multi-Satellite Retrievals for GPM (IMERG) produces precipitation estimates in the range 60° N-S every half hour at 0.1° resolution. The IMERG precipitation is calibrated to the GPM Microwave Imager/Dual-frequency Precipitation Radar combined product to provide the best possible estimates. IMERG products are produced at three different latencies to accommodate the unique requirements of the various user bases. The "Early" run has a 6-hour latency (for flash flood monitoring, etc.), the "Late" run has a 16-hour latency (for drought monitoring, crop forecasting, etc.) and the "Final" run has a 3-month latency (for research). The "Early" and "Late" data begin in March, 2015 and the "Final" data begin in March 2014. In this study "Early" run dataset has been used, the data is downloaded *via* https://pmm.nasa.gov/data-access/downloads/gpm.

2.6. *IMD rainfall gridded dataset*

IMD rainfall gridded dataset is prepared from daily rainfall data archived at the National Data Centre, IMD, Pune, by using Shepard method (Rajeevan *et al.*, 2006) which uses rainfall records of 6329 stations, with varying periods. Out of these 6329 stations, 537 stations are IMD observatory stations, 522 stations are under the Hydro-meteorology program and 70 are Agriculture meteorological stations. Remaining stations are rainfall-reporting stations maintained by state governments. The dataset is obtained from NSDC, IMD, Pune.

3. Methodology

To validate these rainfall products, a matchup data file is generated by using Collocations between various datasets, where the rainfall values from all datasets are available at the same place and at the same time *i.e.*, at same spatial and temporal resolution (Holl *et al.*, 2010, Singh *et al.*, 2018). Collocation process is essential to compare and validate the results from all datasets.

For 2015 monsoon season, the matchup data file is generated at 0.01° spatial resolution and monthly temporal resolution. To achieve this, HE is brought at 0.01° resolution using Box averaging interpolation scheme, IMD gridded rainfall dataset, GPM (IMERG) and GLDAS2.1 rainfall products are brought at 0.01° resolution using bilinear interpolation scheme. IMSRA is
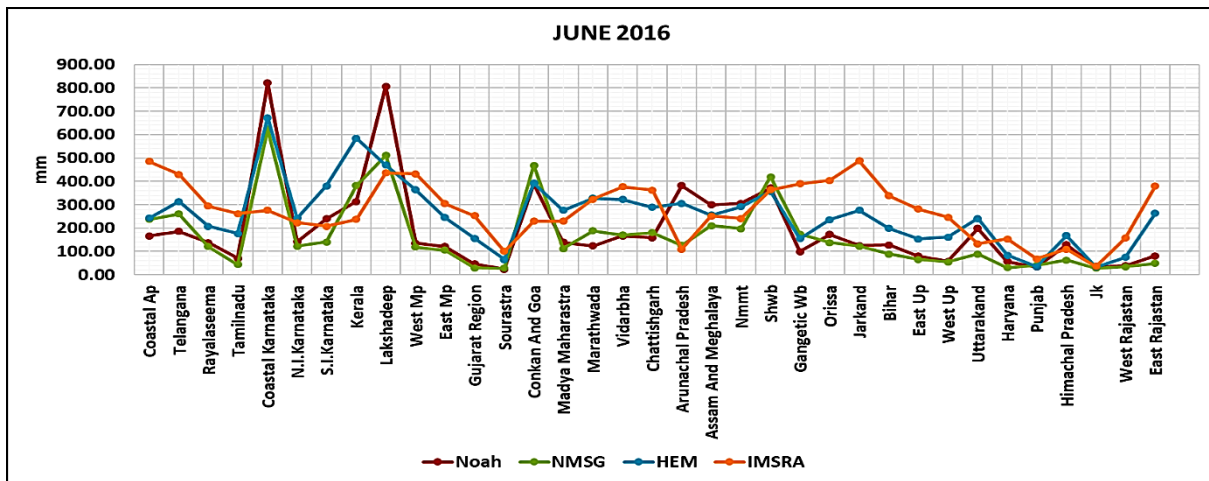
Fig. 1. Monthly accumulated mean over IMD sub-divisions for NMSG; GLDAS2.1; HE; IMSRA respectively for the month of Jun, 2016
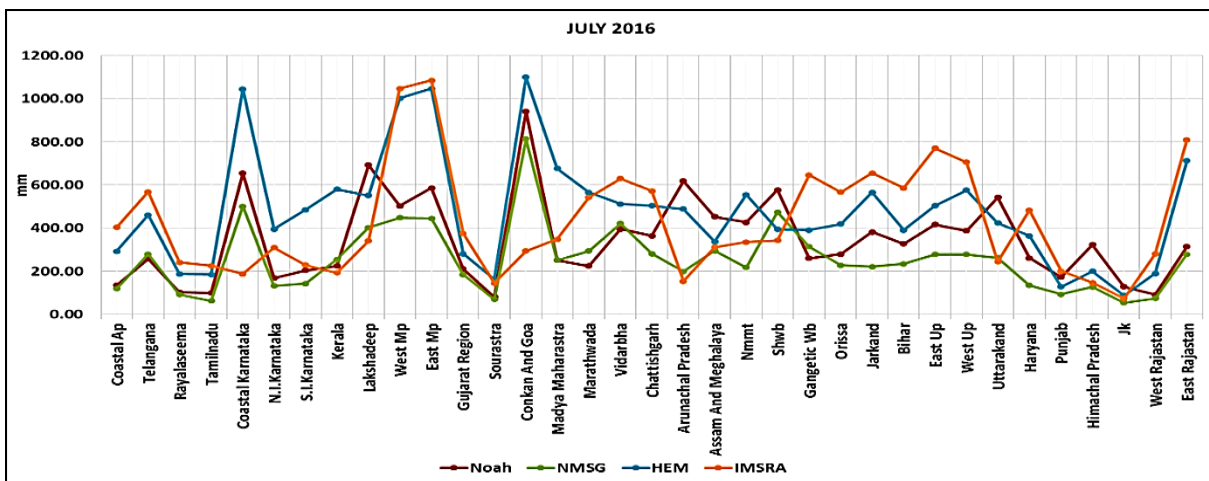

Fig. 2. Monthly accumulated mean over IMD sub-divisions for NMSG; GLDAS2.1; HE; IMSRA respectively for the month of Jul, 2016
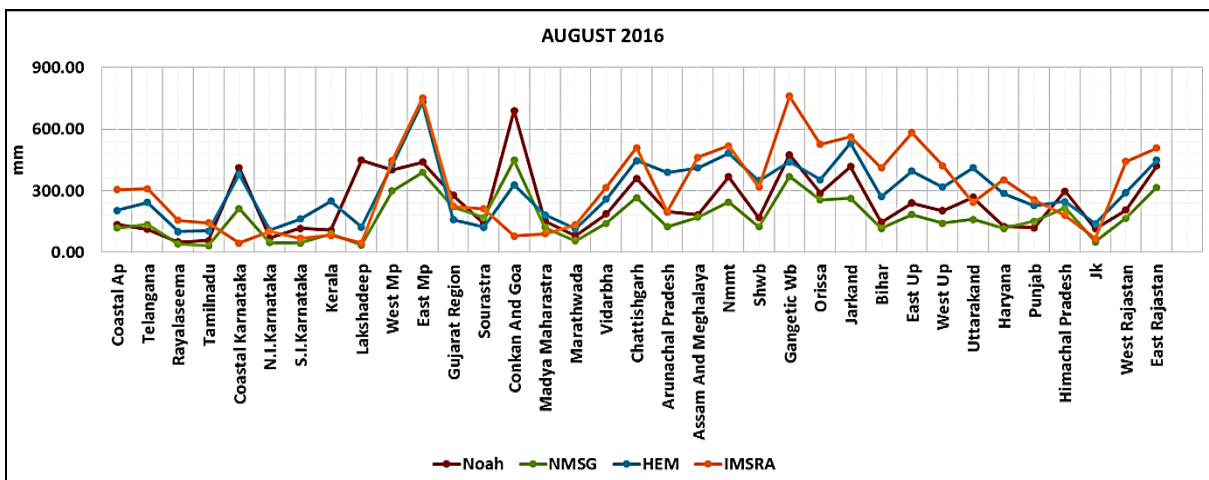

Fig. 3. Monthly accumulated mean over IMD sub-divisions for NMSG; GLDAS2.1; HE; IMSRA respectively for the month of Aug, 2016
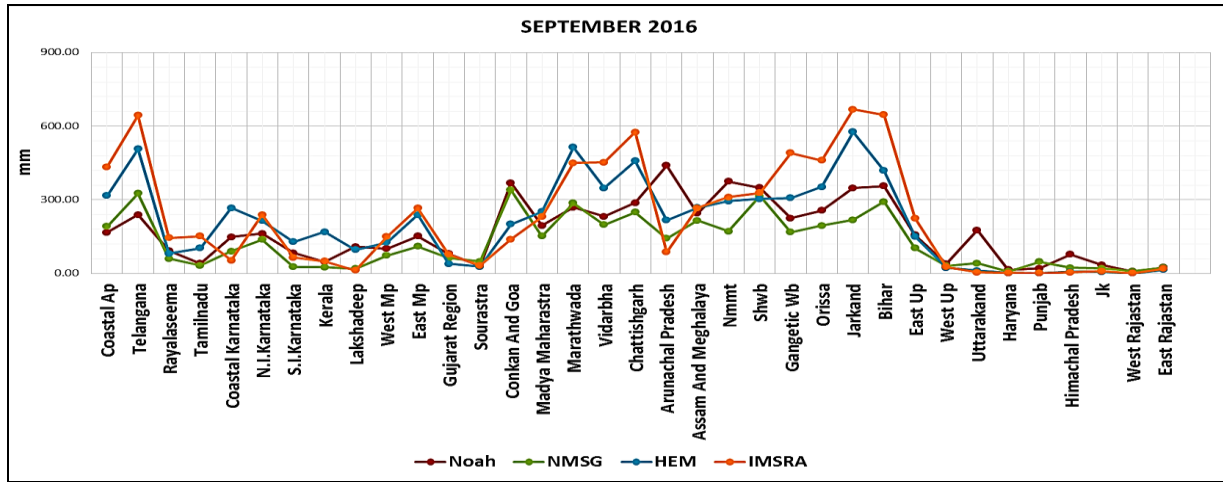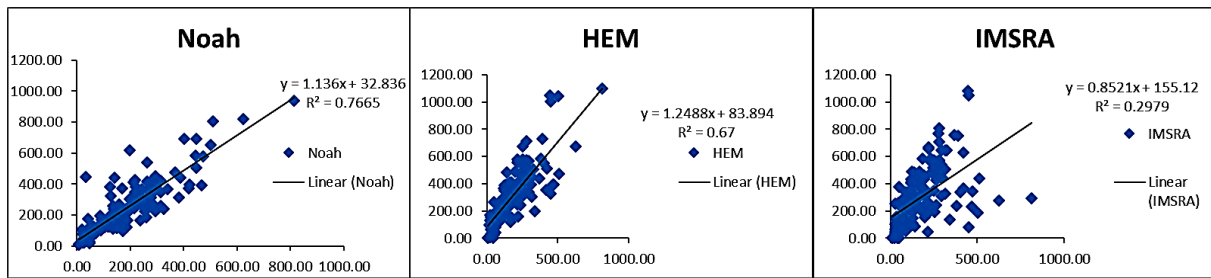
Fig. 4. Monthly accumulated mean over IMD sub-divisions for NMSG; GLDAS2.1; HE; IMSRA respectively for the month of Sep, 2016

Fig. 5(a). Scatter plot of GLDAS2.1 RF Product, HE, IMSRA with NMSG dataset for monsoon Season 2016 (Unit mm)
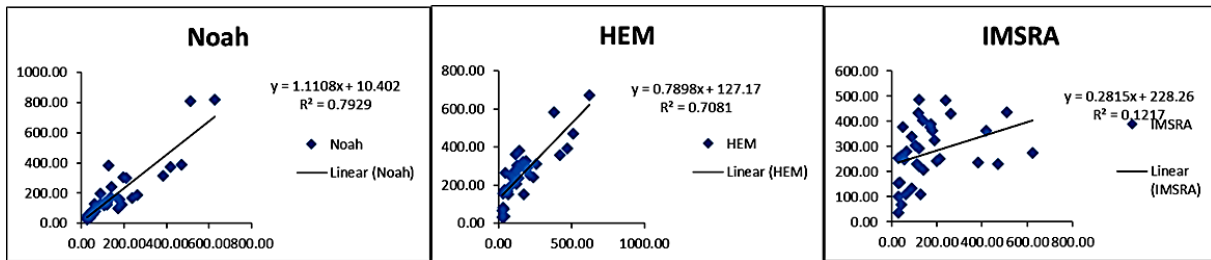
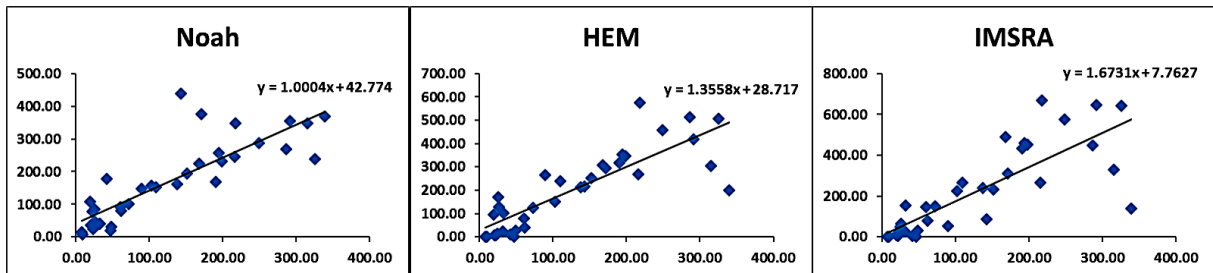**Fig. 5(b).** Scatter plot of GLDAS2.1 RF Product, HE, IMSRA with NMSG dataset for June, 2016 (Unit mm)
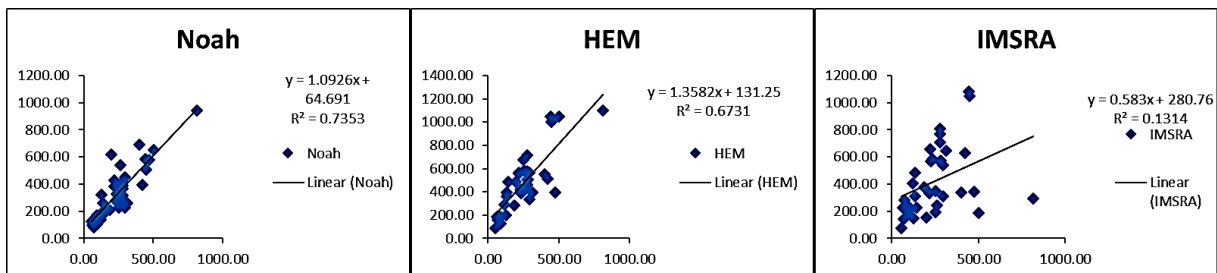
Fig. 5(c). Scatter plot of GLDAS2.1 RF Product, HE, IMSRA with NMSG dataset for July, 2016 (Unit mm)
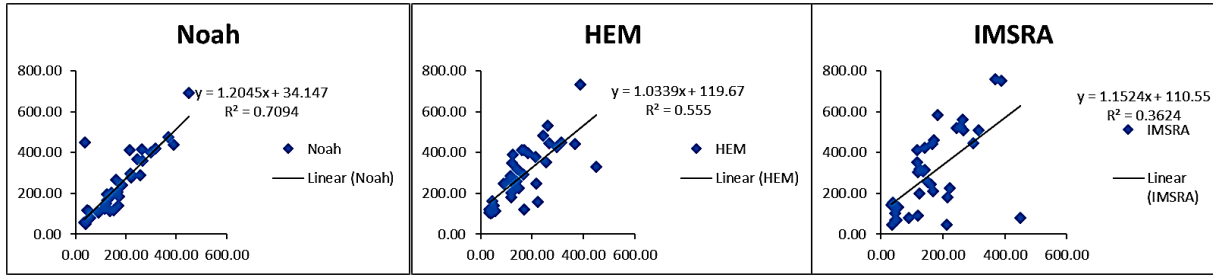
Fig. 5(d). Scatter plot of GLDAS2.1 RF Product, HE, IMSRA with NMSG dataset for August, 2016 (Unit mm)

Fig. 5(e). Scatter plot of GLDAS2.1 RF Product, HE, IMSRA with NMSG dataset for September, 2016 (Unit mm)

generated itself at 0.01° resolution operationally. The monthly accumulated rainfall of IMD gridded rainfall, HE, IMSRA and GPM products are calculated by using daily accumulated rainfall products respectively.

For 2016 monsoon season, the matchup data file is generated at 0.01° spatial resolution and monthly temporal resolution. To achieve this, HE is brought at 0.01° resolution using Box averaging interpolation scheme, NMSG and GLDAS2.1 rainfall products are brought at 0.01° resolution using bilinear interpolation scheme. IMSRA is generated itself at 0.01° resolution operationally. The monthly accumulated rainfall of HE, IMSRA and NMSG products are calculated by using daily accumulated rainfall products respectively.

Using monthly accumulated rainfall estimate products, IMD subdivision wise rainfall maps and bias map with IMD rainfall gridded/NMSG rainfall dataset are prepared for all these rainfall products individually and statistical analysis is carried out in terms of R, R^2 and RMSE. Using these values scatter plots are generated on monthly and seasonal basis over Indian region. Sub division wise zonal monthly accumulated mean is calculated and line graph is plotted for each rainfall product.

4. Results and discussion

The results for the two-successive year's monsoon are discussed below:

4.1. *Monsoon season 2016*

For this study, we have taken NMSG as reference dataset as the IMD-Gridded dataset was not available when this study was done. We have used GNMRP as model derived rainfall estimate dataset, HE and IMSRA as satellite derived rain estimate products. The GPM (IMERGE) calibrated dataset was not available at the time of study therefore it is not used in this section of study.

The onset of monsoon over Andaman and Nicobar Islands was declared on 18th May, 2016 (two days before normal date) and onset over Kerala coast was declared on 8th June, 2016 (seven days after normal date). The pace of advance of this year's monsoon was normal and it covered whole India by 13th July, 2016, nine days before the normal date. The withdrawal of monsoon started from 15th Sept., 2016 and by 28th October, 2016 the SW monsoon had withdrawn from whole of India as declared by IMD.

During monsoon season, Figs. (1-4) depict month wise comparison of various products. GLDAS2.1 Noah Model Rainfall Product (GNMRP) has shown the best fit results with the reference NMSG dataset. It showed very high correlation with NMSG with correlation coefficient (CC) 0.87, R^2 as 0.77 and root mean square error (RMSE) as 105.13 mm for India as a whole as shown in Figs. 5 (a-e). Both heavy and moderate rain events were successfully captured by GNMRP with respect to NMSG dataset. From satellite, derived rainfall estimates products HE showed the best fit results with NMSG dataset. It
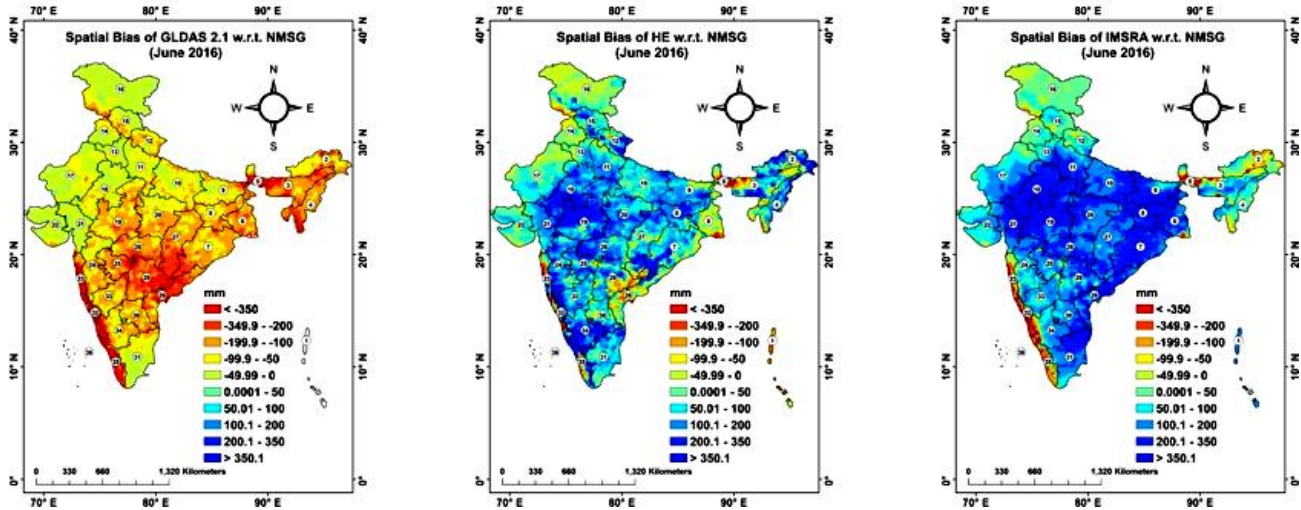
Fig. 6(a). Bias map of June 2016 of GLDAS2.1 RF Product, HE, IMSRA (1st, 2nd, 3rd column respectively) with NMSG dataset
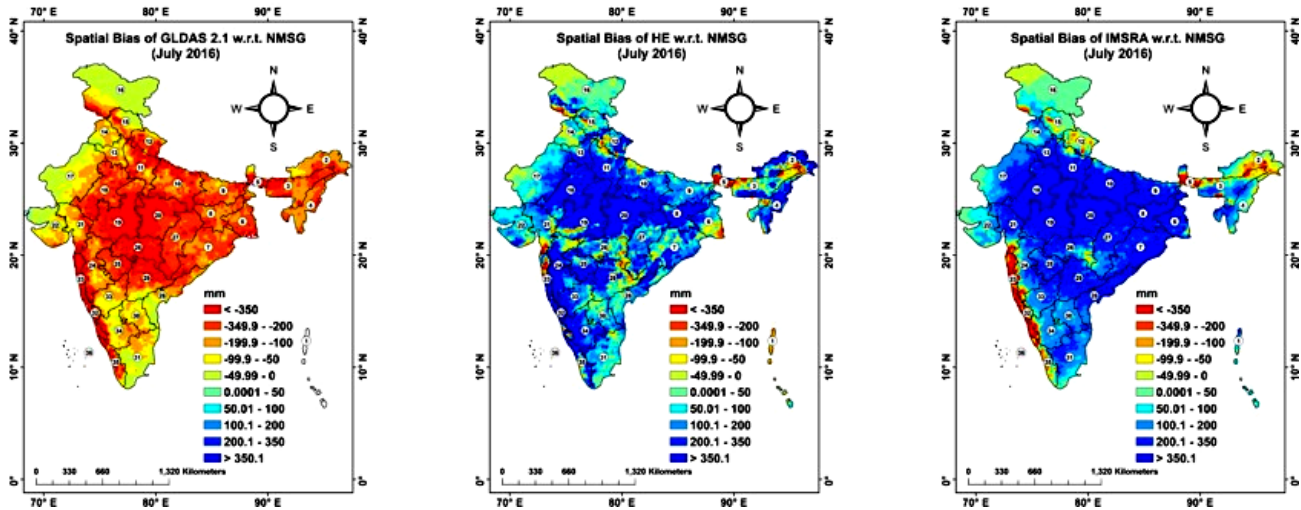

Fig. 6(b). Bias map of July, 2016 of GLDAS2.1 RF Product, HE, IMSRA (1st, 2nd, 3rd column respectively) with NMSG dataset
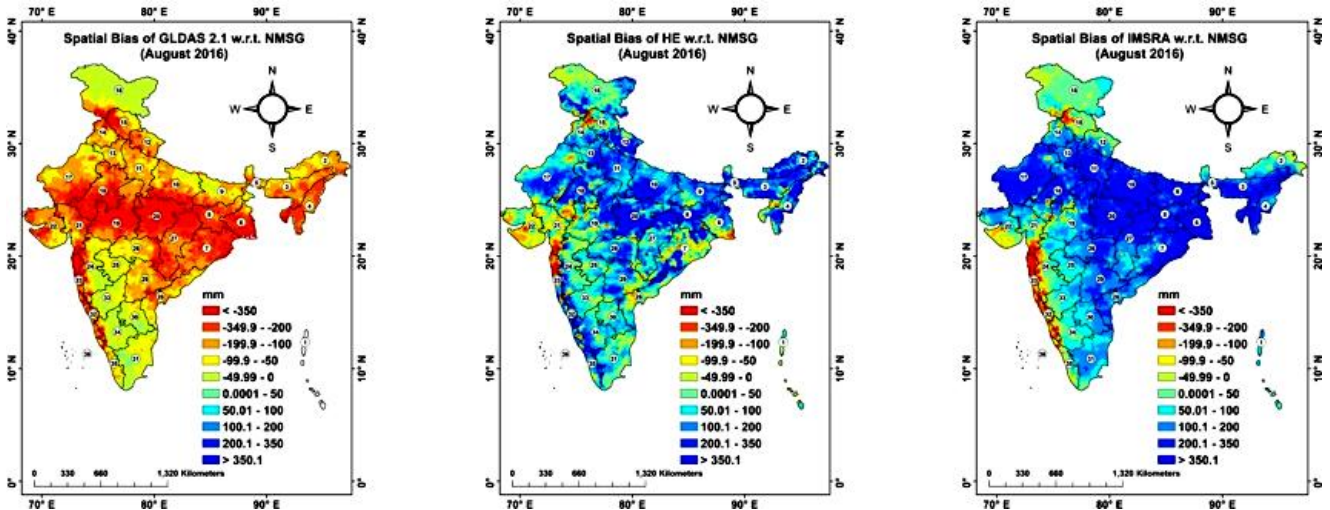

Fig. 6(c). Bias map of August, 2016 of GLDAS2.1 RF Product, HE, IMSRA (1st, 2nd, 3rd column respectively) with NMSG dataset
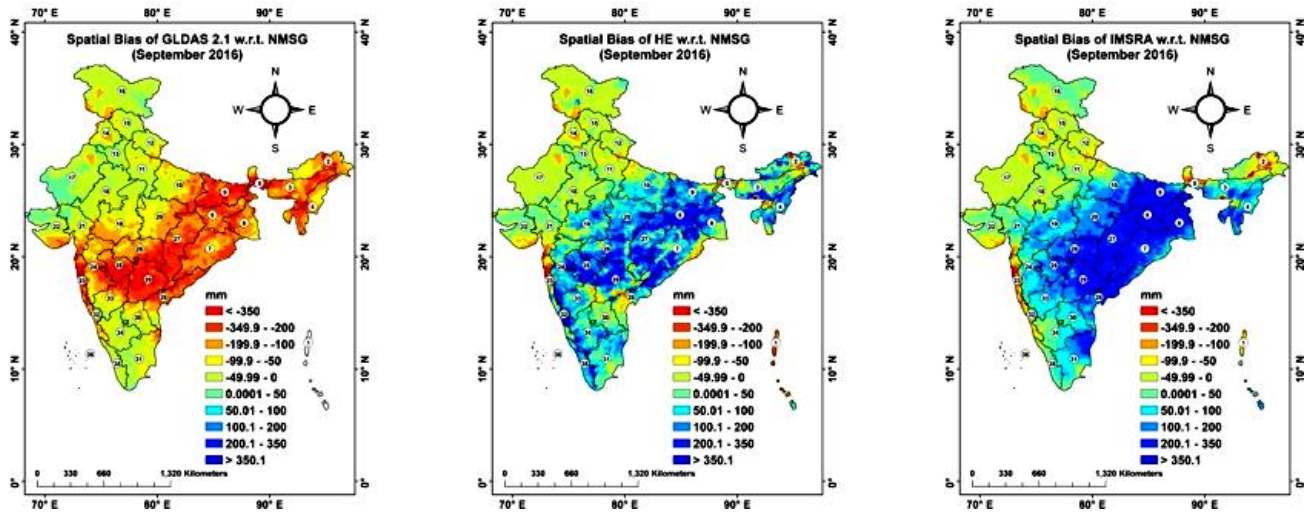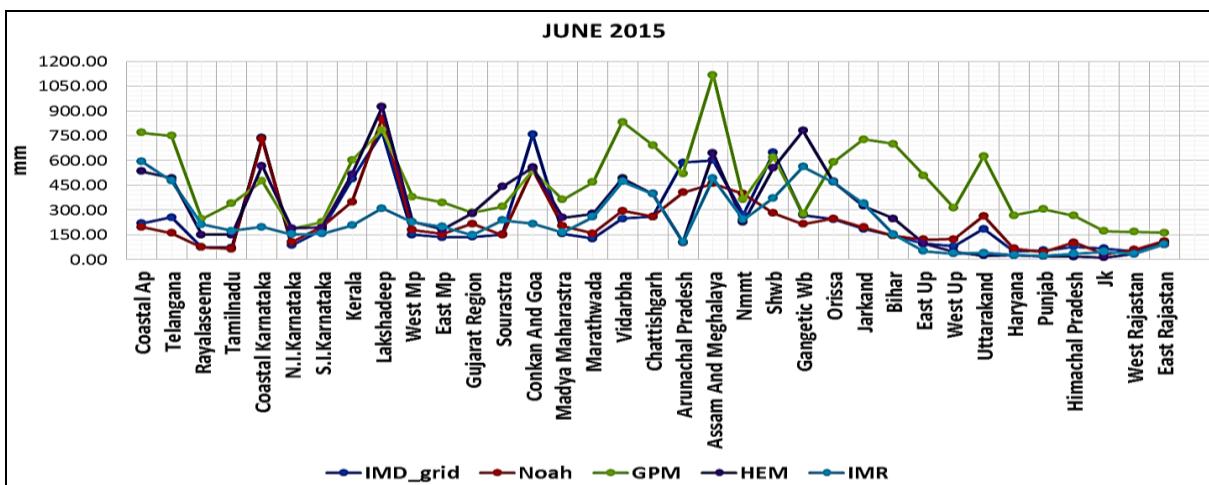
Fig. 6(d). Bias map of September, 2016 of GLDAS2.1 RF Product, HE, IMSRA (1st, 2nd, 3rd column respectively) with NMSG dataset

Fig. 7. Monthly accumulated mean over IMD sub-divisions for NMSG; GLDAS2.1; HE; IMSRA respectively for the month of Jun, 2015
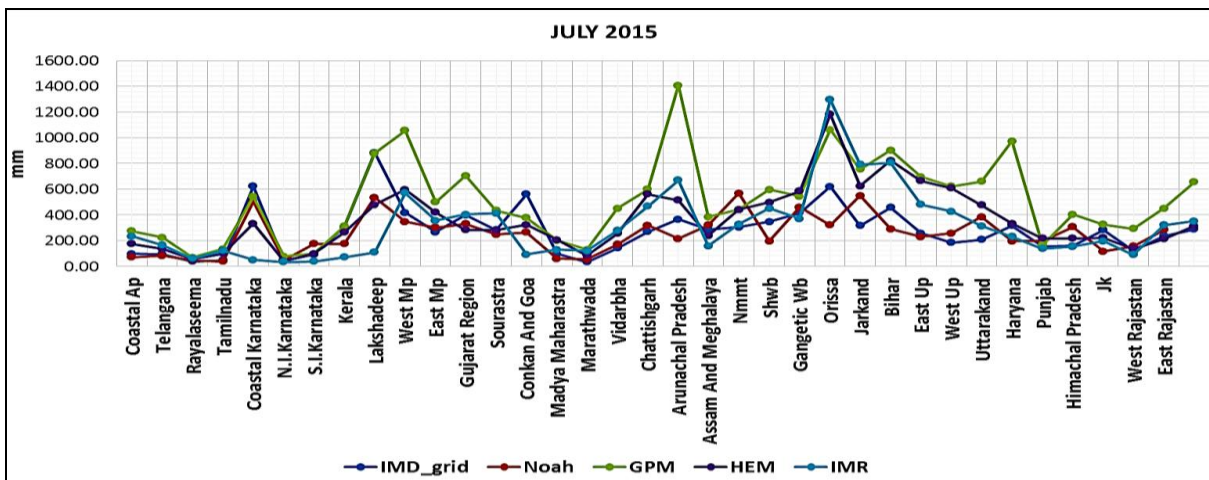

Fig. 8. Monthly accumulated mean over IMD sub-divisions for NMSG; GLDAS2.1; HE; IMSRA respectively for the month of Jul, 2015
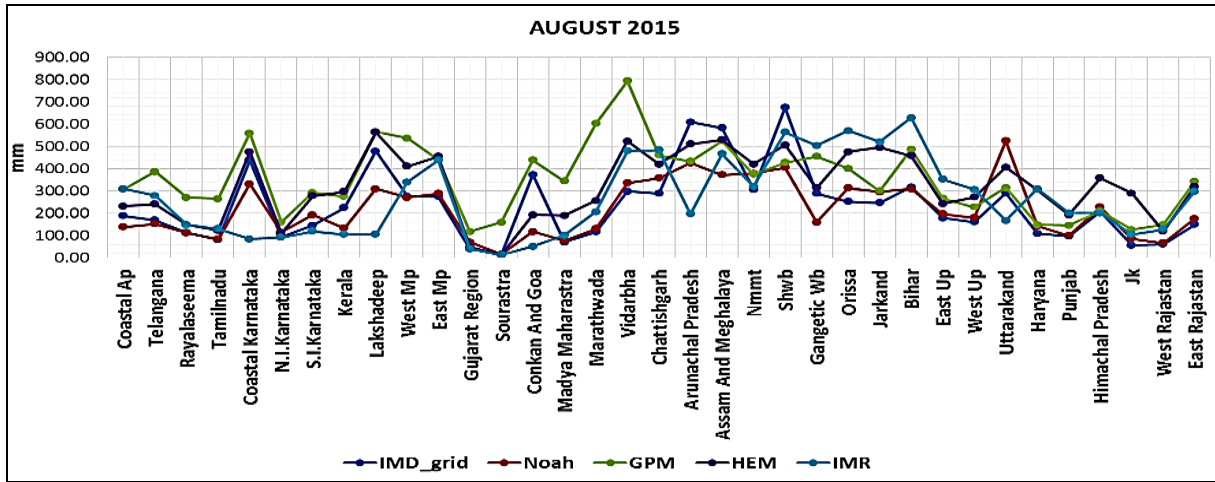
Fig. 9. Monthly accumulated mean over IMD sub-divisions for NMSG; GLDAS2.1; HE; IMSRA respectively for the month of Aug, 2015
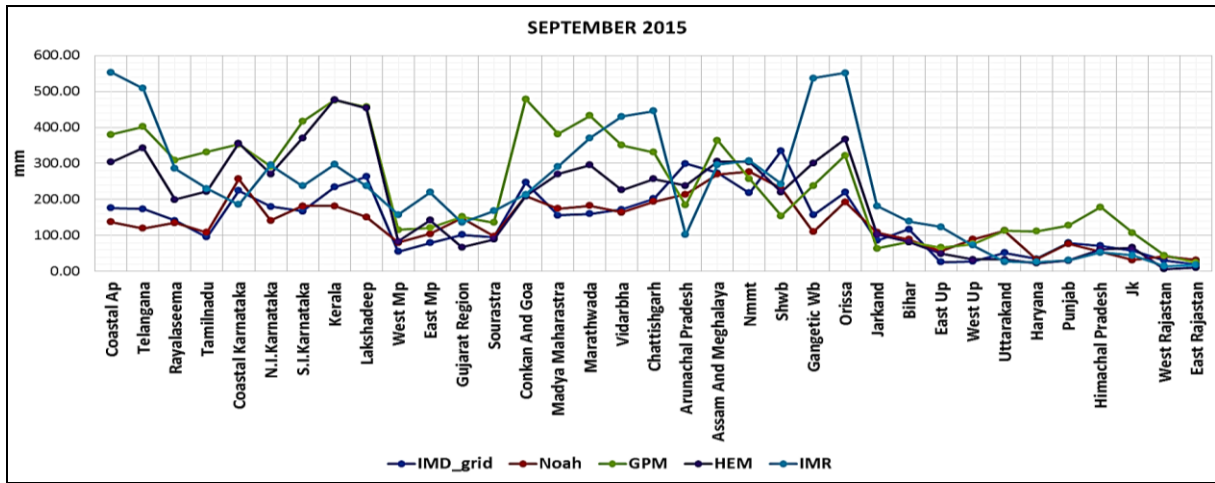

Fig. 10. Monthly accumulated mean over IMD sub-divisions for NMSG; GLDAS2.1; HE; IMSRA respectively for the month of Sep, 2015
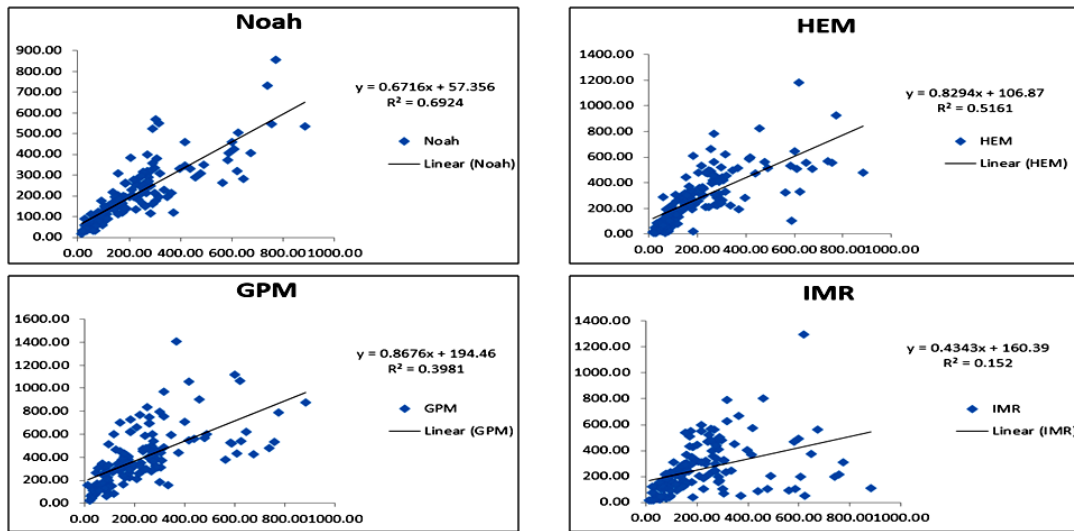

Fig. 11(a).   Scatter plot of GLDAS2.1 RF Product, HE, GPM (IMERG) & IMSRA with IMD gridded rainfall dataset for monsoon season 2015 (Unit mm)
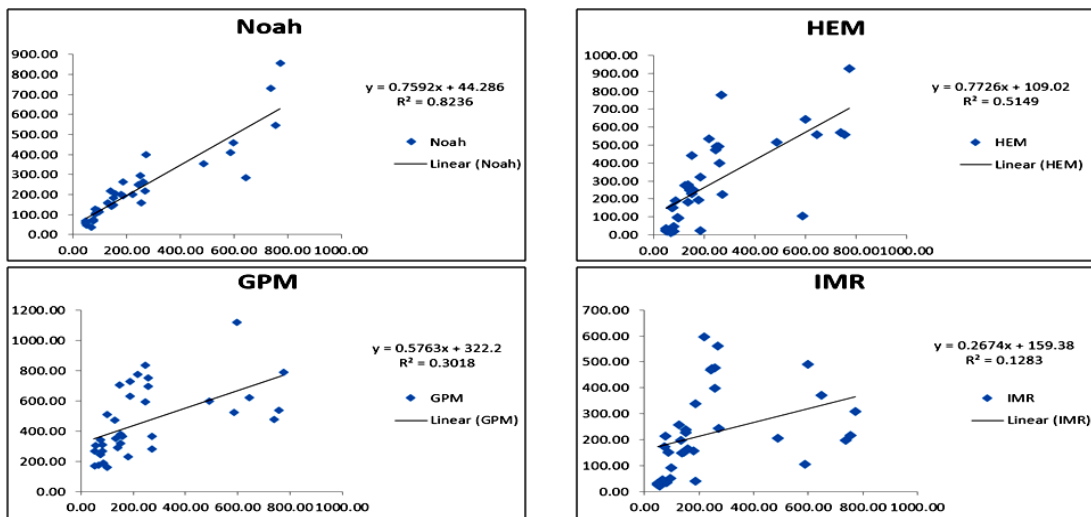
Fig. 11(b). Scatter plot of GLDAS2.1 RF Product, HE, GPM (IMERG) & IMSRA with IMD gridded R/F dataset for Jun, 2015
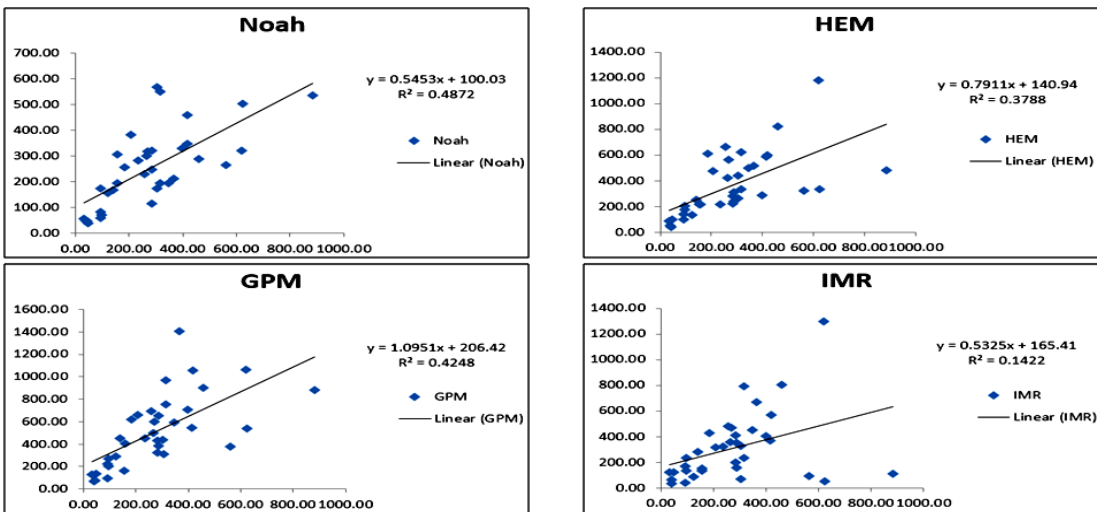

Fig. 11(c). Scatter plot of GLDAS2.1 RF Product, HE, GPM (IMERG) & IMSRA with IMD gridded R/F dataset for Jul, 2015
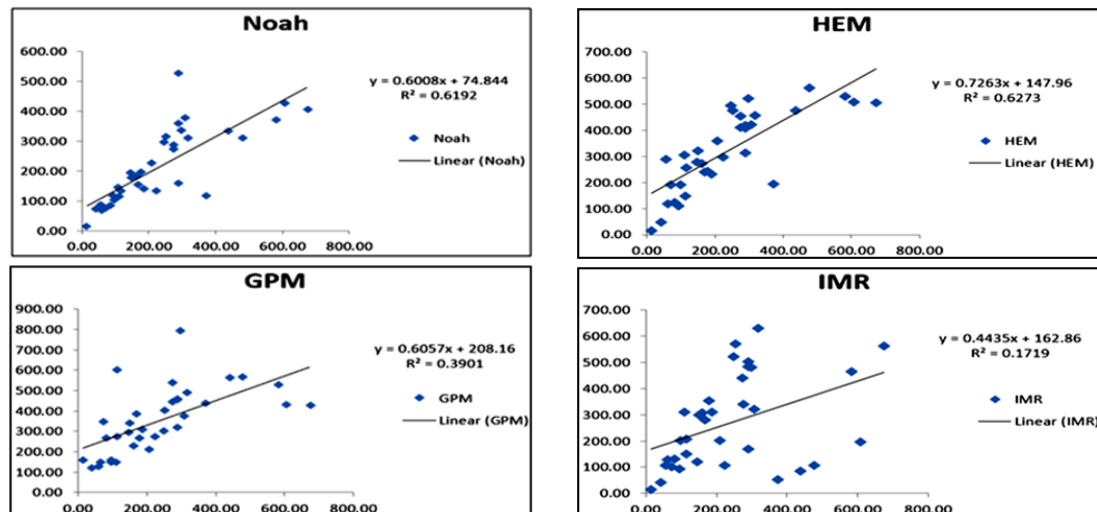

Fig. 11(d). Scatter plot of GLDAS2.1 RF Product, HE, GPM (IMERG) & IMSRA with IMD gridded R/F dataset for Aug, 2015
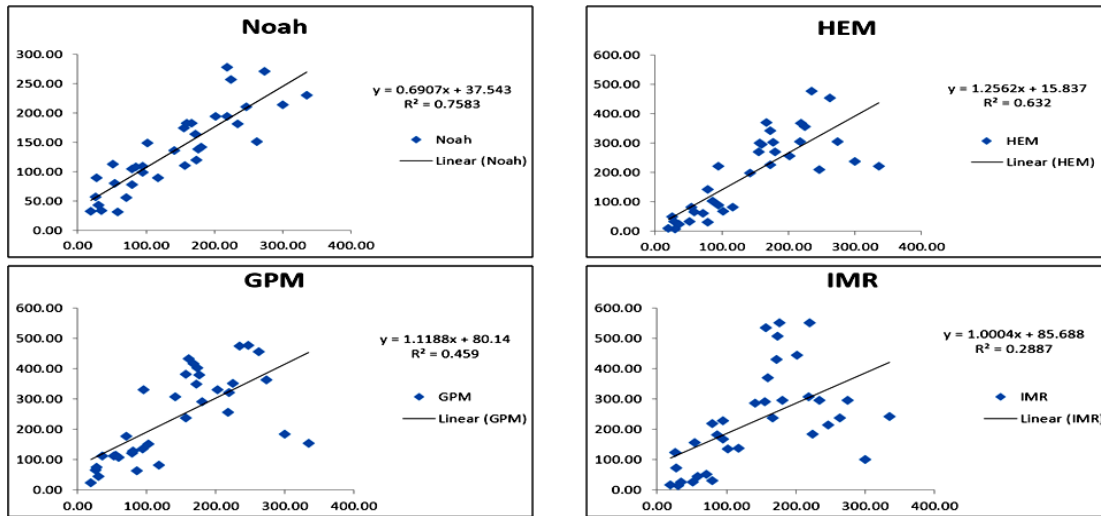
Fig. 11(e). Scatter plot of GLDAS2.1 RF Product, HE, GPM (IMERG) & IMSRA with IMD gridded R/F dataset for Sep, 2015 (Unit mm)

showed very high correlation with NMSG with CC 0.81, R^2 as 0.67 and root mean square error (RMSE) as 179.52 mm for India as a whole as shown in Fig. 5 (a). Both heavy and moderate rain events were successfully captured by GNMRP with respect to NMSG dataset.

4.1.1. *June*

The comparison of various rain products with NMSG is shown in Fig. 1 over IMD's sub-division. In the month of June GNMRP shows the best fit results with NMSG with CC of 0.89, R^2 as 0.79 and RMSE as 89.41 mm for India as a whole [Fig. 5(b)]. Among satellite derived products the HE product shows very good results with NMSG with very high CC of 0.84, R^2 as 0.71 and RMSE as 122.54 mm [Fig. 5(b)]. Both GNMRP and HE had successfully captured heavy and moderate rain events during June month [bias maps Fig. 6(a)].

4.1.2. *July*

The comparison of various rain products with NMSG is shown in Fig. 2 over IMD's sub-division. In the month of July GNMRP shows the best fit results with NMSG with CC of 0.86, R^2 as 0.74 and RMSE as 135.31 mm for India as a whole [Fig. 5(c)]. Among satellite derived products the HE product shows very good results with NMSG with very high CC of 0.82, R^2 as 0.67 & RMSE as 272.42 mm [Fig. 5(c)]. Both GNMRP & HE had successfully captured heavy and moderate rain events during July month. The correlation of both GNMRP and HE with NMSG had decreased in the month of July but the RMSE had reduced suggesting a relative improvement in the estimation of rainfall [bias maps Fig. 6(b)].

4.1.3. *August*

The comparison of various rain products with NMSG is shown in Fig. 3 over IMD's sub-division. In the month of August GNMRP shows the best fit results with NMSG with CC of 0.84, R^2 as 0.71 and RMSE as 108 mm for India as a whole [Fig. 5(d)]. Among satellite derived products the HE product shows very good results with NMSG with high CC of 0.74, R^2 as 0.56 and RMSE as 158.08 mm [Fig. 5(d)]. The correlation of both GNMRP and HE with NMSG had decreased in the month of August but the RMSE had reduced suggesting a relative improvement in the estimation of rainfall [bias maps Fig. 6(c)].

4.1.4. *September*

The comparison of various rain products with NMSG is shown in Fig. 4 over IMD's sub-division. In the month of September GNMRP shows the best fit results with NMSG with a very high CC of 0.84, R^2 as 0.70 and RMSE as 79 mm for India as a whole [Fig. 5(e)]. Among satellite derived products the HE product shows very good results with NMSG with high CC of 0.84, R^2 as 0.71 and RMSE as 121.22 mm [Fig. 5(e)]. The correlation of both GNMRP and HE with NMSG had increased in the month of September, also the RMSE had reduced suggesting a relative improvement in the estimation of rainfall [bias maps Fig. 6(d)].

4.2. *Monsoon season 2015*

For this study, we have taken IMD-Gridded dataset as reference dataset. We have used GNMRP as model derived rainfall estimate dataset, GPM (IMERGE), HE and IMSRA as satellite derived rain estimate products.
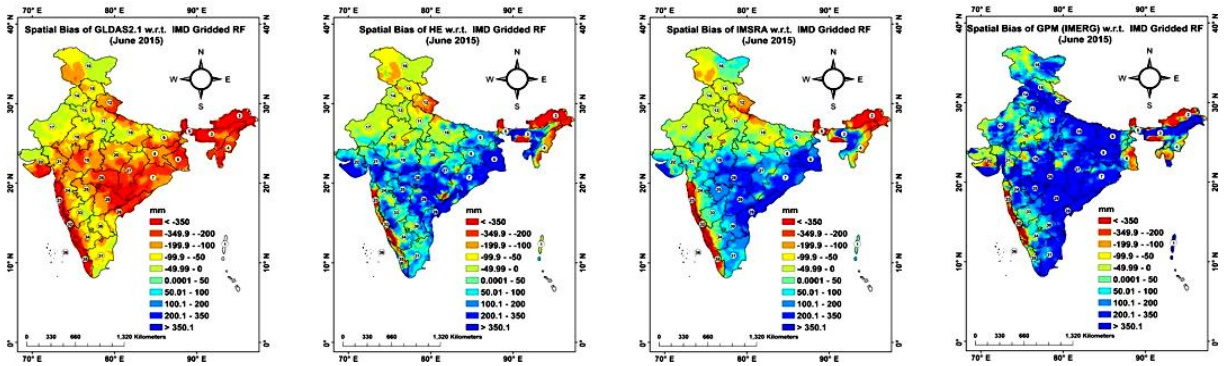
Fig. 12(a). Bias map of June, 2015 (Monsoon) of GLDAS2.1 RF Product, HE, IMSRA and GPM (IMERG) respectively with IMD gridded rainfall dataset
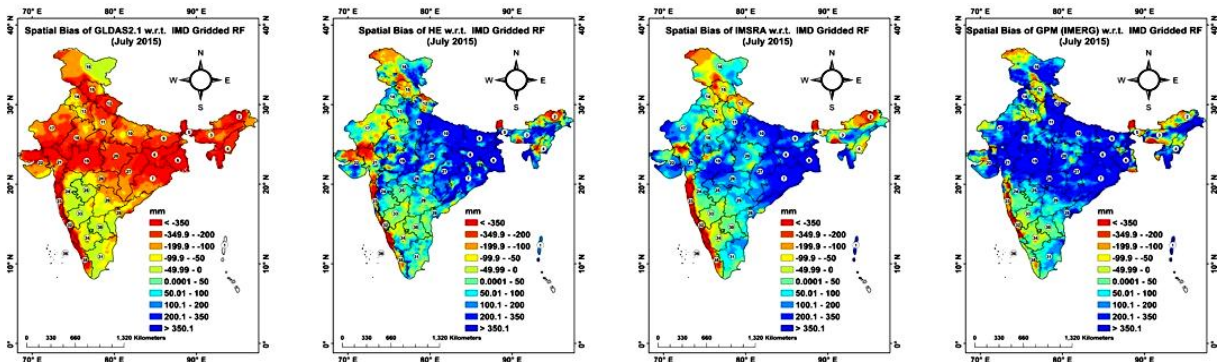

Fig. 12(b). Bias map of July, 2015 (Monsoon) of GLDAS2.1 RF Product, HE, IMSRA and GPM (IMERG) respectively with IMD gridded rainfall dataset
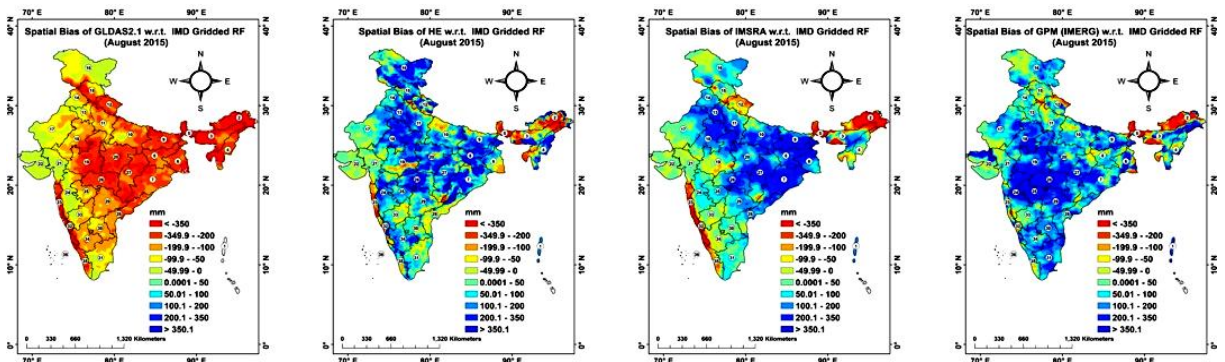

Fig. 12(c). Bias map of August, 2015 (Monsoon) of GLDAS2.1 RF Product, HE, IMSRA and GPM (IMERG) respectively with IMD gridded rainfall dataset
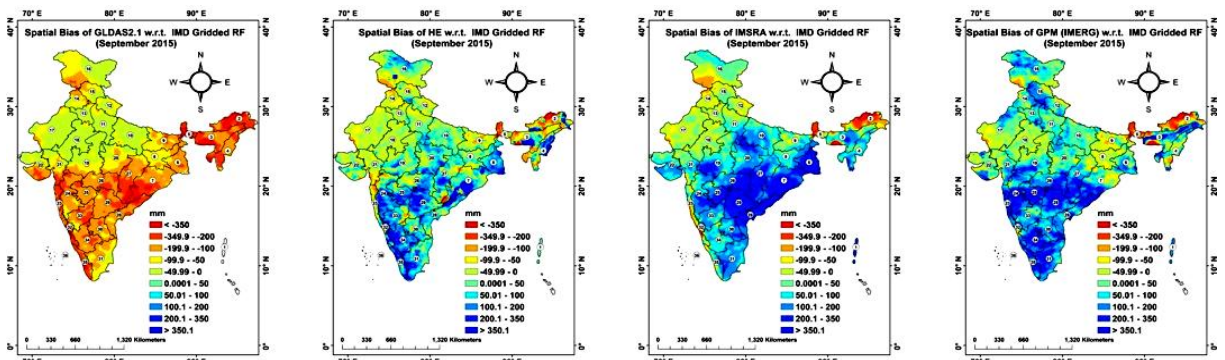

Fig. 12(d). Bias map of September, 2015 (Monsoon) of GLDAS2.1 RF Product, HE, IMSRA and GPM (IMERG) respectively with IMD gridded rainfall dataset

The onset of monsoon over Andaman and Nicobar Islands was declared on 16th May, 2015 (four days before normal date) and onset over Kerala coast was declared on 5th June, 2015 (four days after normal date) by IMD. The pace of advance of this year's monsoon was very fast and it covered whole India by 26th June, 2015. The withdrawal of monsoon started from 4th September, 2015 and by 19th October, 2015 the SW monsoon had withdrawn from whole of India as declared by IMD.

During monsoon season as a whole the GLDAS2.1 Noah Model Rainfall Product (GNMRP) has shown the best fit results with the reference IMD-Gridded dataset. It showed very high correlation with IMD-Gridded with correlation coefficient (CC) 0.83 and root mean square error (RMSE) as 100.05 mm for India as a whole as shown in Fig. 11(a). Both heavy and moderate rain events were successfully captured by GNMRP with respect to IMD-Gridded dataset. From satellite, derived rainfall estimates products HE showed the best fit results with IMD-Gridded dataset. It showed very high correlation with IMD-Gridded with CC 0.72, R^2 as 0.52 and root mean square error (RMSE) as 160.94 mm for India as a whole as shown in Fig. 11(a). Both heavy and moderate rain events were successfully captured by GNMRP with respect to IMD-Gridded dataset.

4.2.1. *June*

The comparison of various rain products with IMD-Gridded dataset is shown in Fig. 7 over IMD's sub-division. In the month of June GNMRP shows the best fit results with IMD-Gridded dataset with CC of 0.91, R^2 as 0.82 and RMSE as 94.11 mm [Fig. 11(b)]. Among satellite derived products the HE product shows very good results with IMD-Gridded dataset with CC of 0.72, R^2 as 0.51 and RMSE as 178.59 mm [Fig. 11(b)]. Both GNMRP and HE had successfully captured heavy and moderate rain events during June month [bias maps Fig. 12(a)].

4.2.2. *July*

The comparison of various rain products with IMD-GRIDDED DATASET is shown in Fig. 8 over IMD's sub-division. In the month of July GNMRP shows the best fit results with IMD-GRIDDED DATASET with CC of 0.70, R^2 as 0.49 and RMSE as 137.90 mm [Fig. 11(c)]. Among satellite derived products the HE product shows very good results with IMD-GRIDDED DATASET with CC of 0.62, R^2 as 0.38 and RMSE as 211.65 mm [Fig. 11(c)]. Both GNMRP and HE had successfully captured heavy and moderate rain events during July month. The correlation of both GNMRP and HE with IMD-GRIDDED DATASET had decreased in the month of July but the RMSE had reduced suggesting a relative

improvement in the estimation of rainfall. The results during the month of July have deteriorated [bias map Fig. 12(b)] as there was a change in the algorithms of HE and IMSRA in mid-July.

4.2.3. *August*

The comparison of various rain products with IMD-GRIDDED DATASET is shown in Fig. 9 over IMD's sub-division. In the month of August GNMRP shows the best fit results with IMD-GRIDDED DATASET with CC of 0.79, R^2 as 0.62 and RMSE as 101.64 mm [Fig. 11(d)]. Among satellite derived products the HE product shows very good results with IMD-GRIDDED DATASET with CC of 0.79, R^2 as 0.63 and RMSE as 130.53 mm [Fig. 11(d)]. The correlation of both IMSRA and HE with IMD-GRIDDED DATASET had increased in the month of August after the changes in algorithm, also the RMSE had reduced suggesting a relative improvement in the estimation of rainfall which can be seen in bias maps [Fig. 12(c)].

4.2.4. *September*

The comparison of various rain products with IMD-GRIDDED DATASET is shown in Fig. 10 over IMD's sub-division. In the month of September GNMRP shows the best fit results with IMD-GRIDDED DATASET with CC of 0.87, R^2 as 0.76 and RMSE as 42.84 mm [Fig. 11(e)]. Among satellite derived products the HE product shows very good results with IMD-GRIDDED DATASET with CC of 0.80, R^2 as 0.63 and RMSE as 99.38 mm [Fig. 11(e)]. The correlation of both GNMRP and HE with IMD-GRIDDED DATASET had further increased in the month of September, also the RMSE had reduced suggesting a relative improvement in the estimation of rainfall which can be seen in bias maps [Fig. 12(d)].

5.   Conclusions

In this study, three satellite derived rainfall estimates *viz.*, HEM, IMSRA & GPM (IMERGE), along with rainfall product of GLDAS2.1 Noah Model; were evaluated with IMD rain gauge based gridded data *viz.*, IMD-GRIDDED Dataset for the year 2015 and NMSG Dataset for the year 2016 over the Indian region at a monthly time scale. The GLDAS2.1 derived Rainfall Product has exhibited best results among all with both IMD-GRIDDED Dataset & NMSG Dataset *i.e.*, CC 0.83, R^2 0.69 & RMSE 100.05 mm and CC 0.87, R^2 0.77 & RMSE 105.13 mm respectively. The same is reflected in the bias maps also. Among the three-satellite derived rainfall estimates HE has exhibited best results with both IMD-GRIDDED Dataset & NMSG Dataset *i.e.*, CC 0.72,

R^2 0.52 & RMSE 160.94 mm and CC 0.81, R^2 0.67 & RMSE 179.52 mm respectively as shown in bias maps. It can be seen that HE performs better especially in hilly terrains like Western Ghats and NE hilly regions (bias maps). This study has increased the confidence level for HE & IMSRA. The outcomes of this study will be used for further improvements in respected rain estimate algorithms. The possibility may be explored for using IMSRA/HE rainfall estimated product to generate NMSG dataset operationally in place of GPM (IMERG) to get better quality of rainfall products. Further event wise and category wise analysis will be carried out on daily and weekly time scale.

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