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Assessment of INSAT-based rainfall products over meteorological subdivisions of India

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सार – मौसम विज्ञान, कृषि, आपदा तैयारियों और जल प्रबंधन के लिए विश्वसनीय और निकट-वास्तविक समय (Near-real-time) की वर्षा की जानकारी आवश्यक है। सैटेलाइट-आधारित वर्षा अनुमान एक विस्तृत क्षेत्र में वर्षा की निरंतर निगरानी करने में अत्यधिक उपयोगी हैं। हालांकि, सैटेलाइट सेंसर की क्षमताओं और एल्गोरिदम के आधार पर, ये अनुमान भिन्न हो सकते हैं और इनकी कुछ सीमाएँ होती हैं। इस अध्ययन में, हमने वर्ष 2021 और 2022 के मानसून मौसम के दौरान भारत मौसम विज्ञान विभाग (IMD) के धरातलीय मापों के साथ तुलना करके, विशेष रूप से इनसैट मल्टी-स्पेक्ट्रल रेनफॉल (IMR) और हाइड्रो-एस्टीमेटर विधि (HEM) पर ध्यान केंद्रित करते हुए, सैटेलाइट-व्युत्पन्न वर्षा अनुमानों का सत्यापन किया है। कृषि योजना, आपदा प्रबंधन और जल संसाधन प्रबंधन के लिए सटीक वर्षा का डेटा अत्यंत महत्वपूर्ण है, जो पूरे भारत में विश्वसनीय वर्षा मापों को सुनिश्चित करने के लिए इस शोध को महत्वपूर्ण बनाता है। हमारा विश्लेषण विभिन्न मैट्रिक्स का अन्वेषण करता है, जिसमें सहसंबंध गुणांक (Correlation coefficients), रूट मीन स्क्वायर त्रुटि (RMSE), और पूर्वाग्रह स्कोर (Bias scores) शामिल हैं, ताकि यह मूल्यांकन किया जा सके कि IMR और HEM दैनिक वर्षा के प्रतिरूपों को कितनी अच्छी तरह दर्ज करते हैं।

विश्लेषण से पता चलता है कि IMR, HEM की तुलना में IMD डेटा के साथ अधिक मजबूत सहसंबंध दर्शाता है, हालांकि दोनों उत्पादों के प्रदर्शन में महत्वपूर्ण क्षेत्रीय भिन्नताएँ हैं। RMSE विश्लेषण से संकेत मिलता है कि IMR मध्य और पश्चिमी भारत में अधिक सटीक वर्षा अनुमान प्रदान करता है। हिमालयी क्षेत्र और दक्षिण भारत के कुछ हिस्सों में IMR और HEM में अधिक त्रुटियाँ पाई जाती हैं। पूर्वाग्रह विश्लेषण से यह भी पता चलता है कि IMR और HEM उत्तरी और पश्चिमी भारत में वर्षा का कम अनुमान लगाते हैं और गंगा के मैदानी पश्चिम बंगाल और मध्य भारत जैसे क्षेत्रों में अधिक अनुमान लगाते हैं। ये विसंगतियाँ उपग्रह-आधारित वर्षा अनुमानों की सटीकता बढ़ाने के लिए निरंतर सत्यापन और स्थानीय अंशांकन की आवश्यकता को रेखांकित करती हैं। यह शोध प्रभावी मौसम निगरानी और संबंधित अनुप्रयोगों के समर्थन के लिए उपग्रह-आधारित वर्षा अनुमान तकनीकों में सुधार के महत्व पर प्रकाश डालता है।

ABSTRACT. Reliable and near-real-time rainfall information is essential for meteorology, agriculture, disaster preparedness, and water management. Satellite-based rainfall estimates are highly useful in continuously monitoring rainfall across a wide area. However, based on the satellite sensor capabilities and algorithms, these estimates can vary and have some limitations. In this study, we carried out the validation of satellite-derived rainfall estimates, particularly focusing on the INSAT Multi-spectral Rainfall (IMR) and Hydro-Estimator Method (HEM), by comparing them to ground-based measurements from the India Meteorological Department (IMD) during the monsoon seasons of 2021 and 2022. Accurate rainfall data is crucial for agricultural planning, disaster management, and water resource management, making this research vital for ensuring reliable rainfall measurements across India. Our analysis explores various metrics, including correlation coefficients, root mean square error (RMSE), and bias scores, to evaluate how well IMR and HEM capture daily rainfall patterns.

The analysis reveals that IMR generally shows a stronger correlation with IMD data compared to HEM, though both products exhibit significant regional variations in performance. The RMSE analysis indicates that IMR provides more accurate rainfall estimates in central and western India. IMR and HEM display higher errors in the Himalayan

region and parts of southern India. Bias analysis further reveals that IMR and HEM tend to underestimate rainfall in northern and western India and overestimate it in areas like Gangetic West Bengal and central India. These discrepancies underscore the need for continuous validation and localized calibration of satellite-derived rainfall estimates to enhance their accuracy. This research highlights the importance of improving satellite-based rainfall estimation techniques to support effective weather monitoring and dependent applications.

Key words – INSAT Multi-spectral Rainfall (IMR), Hydro-Estimator Method (HEM), Satellite precipitation validation, Monsoon, IMD gridded data.

1. Introduction

Precipitation in the form of rain is crucial to the earth system and human population, particularly in India where the summer monsoon accounts for over 70% of annual rainfall. Given that India's economy is mainly agricultural and irrigation facilities are limited, rainfall significantly determines crop yields. Furthermore, uneven rainfall distribution across the country increases the risk of both droughts and floods, making it essential to monitor and measure precipitation to aid agricultural, hydrological, and disaster management efforts. Precise assessment of rainfall across temporal and spatial domains plays a critical role in hydro-meteorological and agrometeorological applications and weather monitoring and forecasting activities (Barros and Lang 2003).

Traditionally, rainfall has been measured using rain gauges, considered accurate but suffer from limitations in India due to inadequate spatial coverage, area representation, and maintenance. As precipitation exhibits high spatio-temporal variations, rain gauge measurements fail to capture this variability due to unevenly distributed networks. Also, maintaining high numbers of RG stations over remote areas is difficult and hinders its use in real-time assessment of floods or heavy rainfall events (Hirpa *et al.* 2010). In contrast, satellite-based rainfall estimations provide an advantage by continuously monitoring large areas regardless of weather conditions. Various satellite channels use advanced algorithms to estimate precipitation over a given region. These products are operationally used by the meteorological and disaster management community, providing complete geographic coverage and high temporal resolution (Dinku *et al.*, 2014; Katsanos *et al.*, 2016), which makes them an ideal alternative to ground-based measurements for near-real-time monitoring of rainfall over the entire region of interest. However, these products have limitations due to their derived nature. Therefore, they are validated against ground truth measurements for accuracy before utilising these satellite-derived rainfall products.

Satellite-based rainfall estimation utilizes geostationary (GEO) and low earth orbit (LEO) satellites. LEO satellites travel in inclined orbits and revisits the same location on the Earth approximately twice daily. The Tropical Rainfall Measuring Mission (TRMM) (Simpson *et al.* 1996) was the most widely used satellite mission

dedicated to precipitation measurements for the last two decades. It played a key role in developing new satellite-based rainfall estimation techniques, employing a range of passive and active sensors that allowed for a comparison between them. A relationship was derived between the sensors, which was then used in satellites with only passive sensors. The current operational LEO satellites for rainfall estimations are National Oceanic and Atmospheric Administration (NOAA) and EUMETSAT's MetOp series of satellites. The Defense Meteorological Satellite Program (DMSP) series of satellites also provides rainfall estimation capability based on microwave, IR/VIS channels (Kummerow *et al.*, 2001, 2006). However, microwave-based estimations also have limitations due to uncertainty in hydrometeor/droplet parameters such as shape, orientation, and distribution within the large footprint and the coarser spatiotemporal resolution (Varma and Pal 2012). The spectral resolution of the satellite sensor, types of wavelengths used, type of satellite orbit, scanning speeds, and spatio-temporal resolution are the governing factors that limit rainfall estimates through satellites.

Kidd and Levizzani (2011) discuss different precipitation retrieval techniques based on observations and spectral wavelengths used in satellite-based estimations. A multi-spectral approach is employed to address the limitations of single-band retrievals, using information from more than one spectral channel. For example, the GOES Multi-Spectral Rainfall Algorithm uses five channels from the GOES satellite to extract information about cloud and rain extent, derive rainfall, and apply corrections based on cloud type and precipitation regime. However, approximations are applied to these algorithms to address sensor limitations, resolution, and wavelength used. NWP-derived parameters are also used in most of these rainfall retrieval methods, incorporating intrinsic limitations in the satellite rainfall retrieval products. Hence, continuous validation against ground truth is necessary to maintain the advantages of these products in operational applications.

Recent studies have emphasized the importance of validating satellite-based rainfall estimates to enhance the accuracy and reliability of these products. The validation of satellite-estimated convective rainfall products during the summer cyclone season of 2020 has shown significant insights into their performance and accuracy, as

demonstrated by Sateesh *et al.* (2021) in their comprehensive case study. The INSAT Multi-spectral Rainfall (IMR) estimation technique, derived from the Indian National Satellite System (INSAT) series, has shown promising results in capturing spatio-temporal rainfall patterns. A recent study by Rao *et al.* (2021) performed a comprehensive validation of INSAT IMR against ground-based measurements across various climatic zones in India, highlighting its potential for operational use in meteorological applications. Similarly, the Hydro-Estimator Method (HEM), which utilizes infrared and visible satellite imagery, has been evaluated for its effectiveness in estimating rainfall. Mishra and Gupta (2022) conducted an in-depth analysis of HEM-derived rainfall data, comparing it with gauge observations and other satellite products. Their findings indicate that while HEM provides reasonable estimates, certain biases exist, necessitating continuous refinement and validation. Additionally, Kumar *et al.* (2020) assessed the performance of IMR and HEM during extreme weather events, demonstrating their strengths and limitations in real-time flood monitoring. Singh and Verma (2021) further corroborated these findings by evaluating the accuracy of these methods in different topographical settings. An inter-comparison of satellite-estimated products against the IMD gridded dataset by Tirumani *et al.* (2021) brings out the advantages and limitations of these products. In this study, HEM was observed to perform better than the IMR for various rainfall categories across the homogeneous regions. These recent validations underscore the critical role of satellite-derived rainfall products in supplementing traditional measurement techniques, particularly in regions with sparse ground-based observation networks.

The present study validates the HEM and IMR rainfall products for the entire country to identify the spatial performance in estimating rainfall over meteorological subdivisions of India. The study is performed for two consecutive monsoon seasons to check the consistency of the results. Various statistical methods are used to analyse the performance of these products. This study helps bring out the advantages and limitations of INSAT estimated rainfall products over all the subdivisions of India, thereby helping address the specific regions. It also ensures that operational meteorologists have confidence in these products for real-time rainfall monitoring.

2. Data and methodology

2.1. IMR

IMR rainfall product is derived at $1^\circ \times 1^\circ$ spatial resolution with half-hourly temporal resolution. It is made

available through <https://www.mosdac.gov.in>. IMR uses TIR and water vapour (WV) radiances to classify the cloud categories, such as convective, deep convective, low-level clouds, and cirrus clouds (Roca *et al.* 2002). Filtering of low and non-raining clouds along with warm and semi-transparent clouds is done based on IR and WV, and rainfall is estimated for clouds with brightness temperatures colder than 240K. A Regression relation between TRMM-PR and IR is used to compute the instantaneous rain rate.

2.2. HEM

Hydro-estimator (HEM) is another INSAT derived rainfall estimation product available at pixel-scale (4 km at nadir), half-hourly temporal resolution. The HEM algorithm uses TIR information and numerical forecasts at high spatial and temporal resolutions. Multiple corrections, such as Orographic, dry atmosphere and warm rain corrections, are used in this algorithm (Kumar and Varma 2017). The rain at a pixel is affected by the brightness temperature of the surrounding pixels. This helps in determining the location of the pixel. The IR measurements are blended with NWP model fields at a pixel under consideration for more precise rain detection and measurement. The HE uses infrared (IR) window channel (10.7- μm) brightness temperatures as the main basis for discriminating rain from non-raining areas and for estimating rainfall rates.

2.3. IMD rain gauge and gridded data

IMD receives rainfall data from a network of 3527 stations distributed nationwide. These include Hydro-met, Agro-met and state department-maintained rain gauges. Using these station-wise data, daily rainfall is derived. The distribution of these stations over the country is shown in Fig. 2. Most parts of the country have a fair density of observations except the Himalayan states of Jammu & Kashmir and Arunachal Pradesh. The spatial distribution of these stations is irregular due to various limitations like inaccessible terrain / topography, population density, *etc.* This irregular spatial distribution can influence the accuracy of validation parameters such as correlation and RMSE. In regions with sparse rain gauge coverage - particularly the Himalayan belt, northeastern states, and parts of western India - the ground observations may not fully capture the local variability of rainfall. As a result, satellite estimates validated against limited ground truth in these areas may show lower correlation or higher RMSE, not necessarily due to product inaccuracy but due to the lack of representative in-situ observations. This limitation is important to consider when interpreting performance metrics over data-sparse regions.

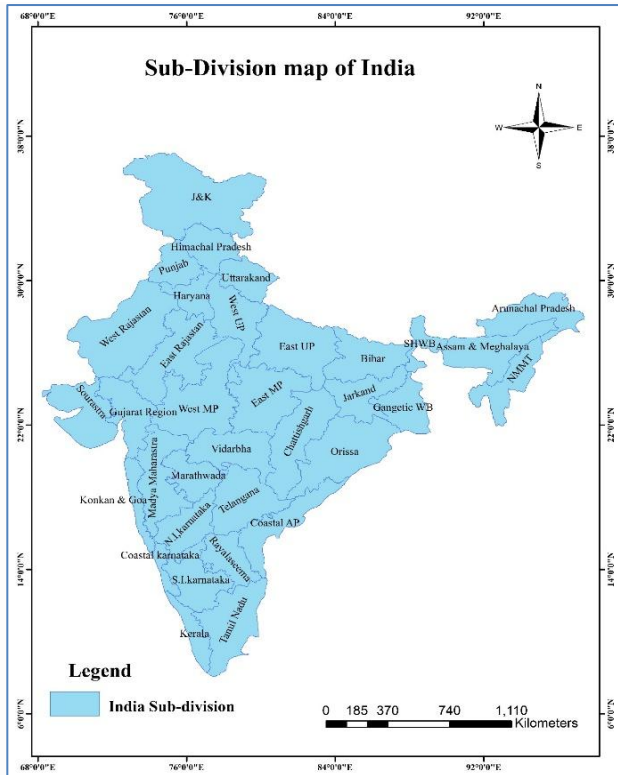


Fig. 1. Sub-division map of India

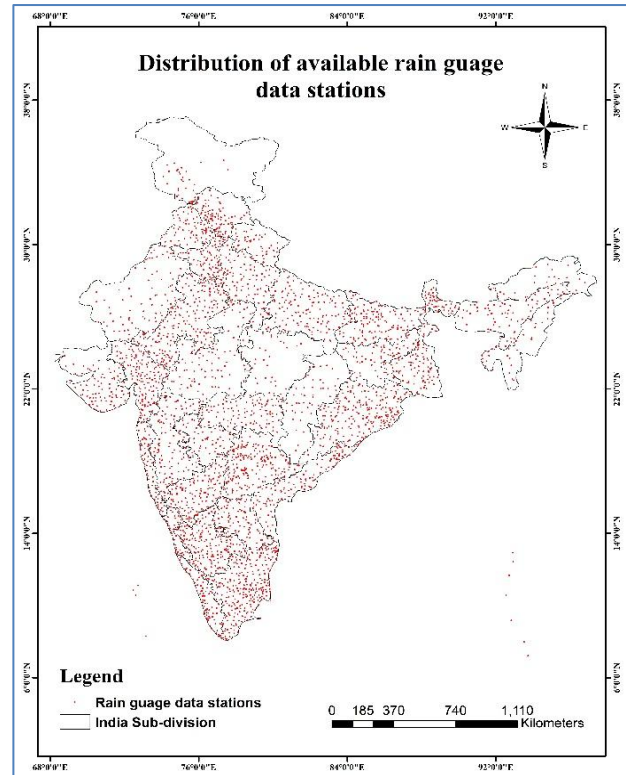


Fig. 2. Spatial Distribution of Rain Gauge

IMD 0.25° gridded rainfall data (Pai *et al.*, 2014) prepared using the rain gauge dataset is also used for daily trend analysis. To ensure the consistency and reliability of the rain gauge data used in this study, only stations that provided continuous daily rainfall records (at least 20 days in a month) during the monsoon seasons of 2021 and 2022 were considered. Stations with significant gaps or inconsistent reporting were excluded from the analysis. Additionally, the 0.25° gridded rainfall dataset, developed by IMD using an objective interpolation scheme (Pai *et al.*, 2014), helps to mitigate the impact of missing data by incorporating information from nearby stations. This approach ensures robustness in the evaluation of satellite products while minimizing the influence of data gaps.

The current study uses these data sets for the Indian summer monsoon period, *i.e.*, June, July, August, and September, Over two years, 2021 and 2022.

2.4. Methodology

India has been divided into 36 subdivisions (Fig 1 & Annexure 1) by India Meteorological Department based on homogeneity of meteorological parameters and considering practical applicability. These subdivisions are different from political divisions as it is divided because

of diverse weather and climate in India. (Kelkar, R. R., & Sreejith, O. P. (2020)).

The rainfall values from IMR and HEM were extracted at station locations using the Geographic Latitude and longitude coordinates of IMD stations. This data is then used for further study. IMR and HEM datasets are available at different spatial resolutions than that of IMD gridded dataset. Hence these datasets were resampled to a common resolution of 0.25 degree.

INSAT-3D-IMR (INSAT Multispectral Rain) and INSAT-3D-HEM, were evaluated against the Indian Meteorological Department rain-gauge data from June-1st to Sep-30th. All India mean rainfall value for each day of monsoon season was calculated for 2021 and 2022. The ocean/sea region is masked in all the satellite products to get the values over land. This was plotted along with IMD gridded rainfall values to analyze the daily trend (Fig. 3 & 4) captured by these datasets.

Evaluation is performed at meteorological subdivisions of India for rainfall variability. Various statistical metrics like mean, bias, correlation coefficient (CC), and root-mean-square error (RMSE) were calculated to evaluate the robustness of satellite

TABLE 1

Datasets used for present study

Dataset	Source	Spatial resolution	Temporal Resolution	Reference
IMD	Rain gauges	0.25°	Daily	Pai (2014)
HEM	IR	0.04°	30 mins	Scofield and Kuligowski (2003) Varma <i>et al</i> (2015)
IMSRA	TIR1, WV, TRMM-PR calibration	0.1°	30 mins	Ba and Gruber (2001) Gairola <i>et al</i> (2010)

precipitation estimates with actual rainfall measurements of IMD gauge-based observations.

3. Results and discussion

3.1. Daily rainfall trend analysis

Daily accumulated Rainfall products averaged over the country (Fig. 3 and 4) show that both HEM and IMR are capturing the daily variability observed in the IMD gauge rainfall data well. Both products closely match themselves; however, at the same time, both products are seen overestimating the rainfall throughout the season.

3.2. Correlation coefficient

The spatial correlation plots are prepared for IMR-IMD and HEM-IMD gauge-based rainfall over India during monsoon months of 2021 & 2022 (Figs. 5 & 6).

During June 2021, the correlation coefficient (CC) between IMR and IMD data was moderate across India, except for the Western Himalayan region (West J&K, Himachal Pradesh, and Uttarakhand), parts of Haryana, West Rajasthan, Gujarat, Konkan Goa, west Madhya Maharashtra, parts of Kerala and Karnataka, north coastal Andhra Pradesh, Jharkhand, Gangetic West Bengal (GWB), and the northeast. The CC between HEM and IMD was generally lower than IMR, with some positive correlation observed, except in parts of J&K, Punjab, Haryana, North MP, East UP, Saurashtra, northern Konkan, western Madhya Maharashtra, western Karnataka, Kerala, south coastal AP, Jharkhand, GWB, Andhra Pradesh, central Assam, Meghalaya, and East NMMT.

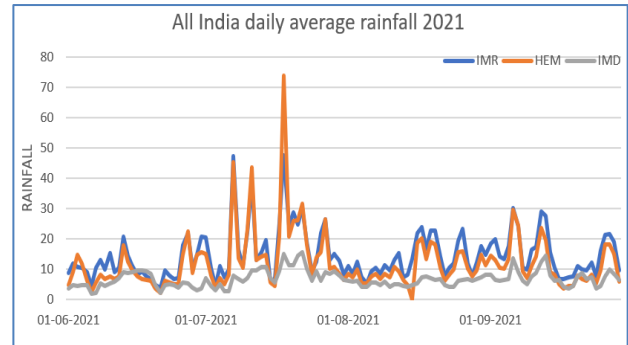


Fig. 3. Time series graph monsoon 2021

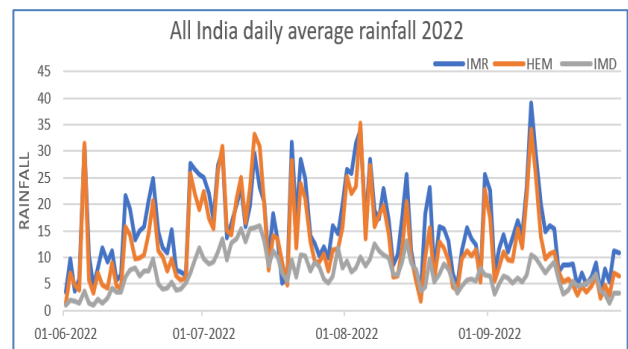


Fig. 4. Time series graph of monsoon 2022

In July 2021, the CC between IMR and IMD was significant in central India, West Rajasthan, coastal Karnataka, and Tamil Nadu, but showed negative correlation in East J&K, East Punjab, parts of Haryana, eastern West Rajasthan, southern Saurashtra, South Gujarat, Madhya Maharashtra, Konkan Goa, Kerala, South Karnataka, scattered parts of North Interior Karnataka, east Tamil Nadu, coastal AP, Bihar, SHWB, West Assam, Meghalaya, West Arunachal, and West NMMT. The CC between HEM and IMD was moderate across the country, slightly higher than IMR, except in West J&K, Punjab, West Haryana, West Uttarakhand, Himachal, eastern West Rajasthan, southern Saurashtra, West UP, northern Konkan, western Madhya Maharashtra, Kerala, Karnataka, Tamil Nadu, coastal AP, East Telangana, Jharkhand, Bihar, and Northeast India.

In August 2021, the CC between IMR and IMD was highly significant in central and west India, but mostly insignificant in West J&K, north Himachal and Punjab, coastal Saurashtra, South India from Konkan to Kerala, Tamil Nadu, coastal AP, Orissa, Jharkhand, South Bihar, SHWB, and northern Arunachal, Assam, and Meghalaya. The CC between HEM and IMD was less significant compared to IMR, showing good correlation in North and central India, with insignificant correlation in West J&K, Punjab, West Himachal, East Uttarakhand, patches in

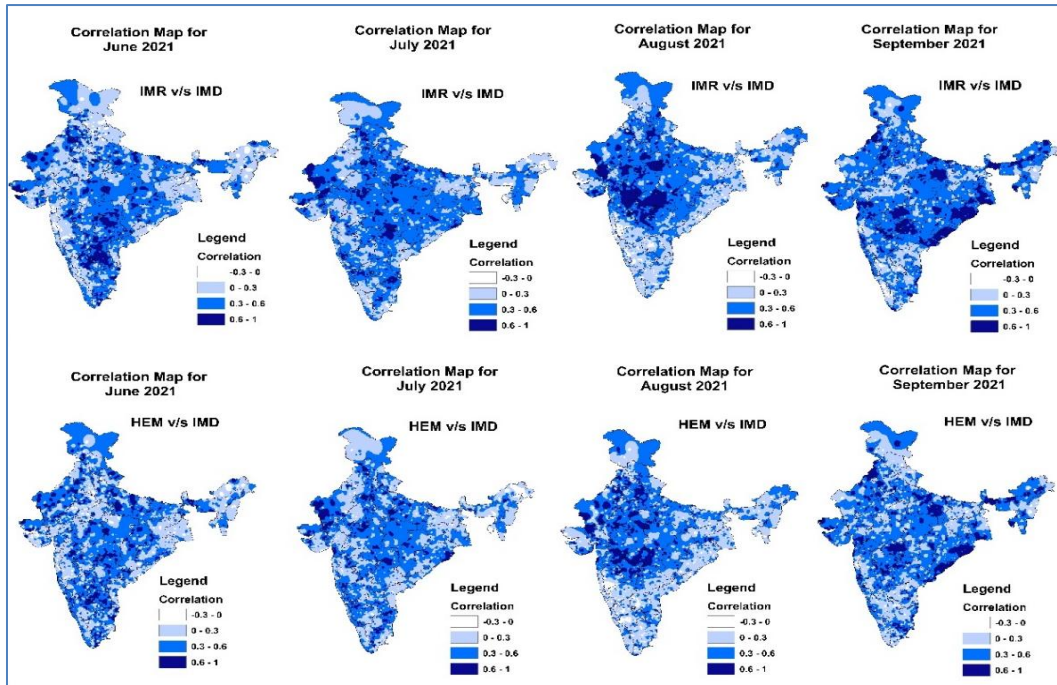


Fig. 5. Correlation plots 2021

western West Rajasthan, West Saurashtra, South India from Konkan to Kerala, Tamil Nadu, Rayalaseema, coastal AP, South Telangana, Orissa, North Jharkhand, South Bihar, East UP, SHWB, northern Arunachal, Assam, and NMMT.

During September 2021, the CC between IMR and IMD was mostly significant across the country, except in central J&K, North Himachal, Uttarakhand, South Haryana, scattered parts of Punjab and West Rajasthan, adjoining East Rajasthan and West MP, North Konkan, western Madhya Maharashtra, North Interior Karnataka, South Interior Karnataka, Kerala, Tamil Nadu, Rayalaseema, south coastal AP, South Bihar, East NMMT, and Arunachal Pradesh. The CC between HEM and IMD showed more negative correlation compared to IMR, with significant areas being South J&K, Himachal Pradesh, Uttarakhand, scattered parts of Punjab, Haryana, West UP, western West Rajasthan, adjoining East Rajasthan and West MP, parts of Gujarat and Saurashtra, North Konkan, western Madhya Maharashtra, North Interior Karnataka, South Interior Karnataka, South Kerala, parts of Tamil Nadu, Rayalaseema, south coastal AP, parts of Telangana, Chhattisgarh, West Jharkhand, Bihar, East GWB, central Assam, Meghalaya, and East NMMT.

During June 2022 (Fig. 6) the correlation coefficient between IMR and IMD station wise data measurements is significant primarily throughout the country Himachal Pradesh, small parts of Haryana and Punjab, south of east

UP, East part of west Rajasthan and adjoining East Rajasthan, North Gujarat region, West Sourashtra, West of west MP, Konkan Goa, west of Madhya Maharashtra, Coastal Karnataka, adjoining parts of Kerala and Karnataka, parts of Tamil Nadu, south Telangana central costal AP, costal parts of Orrisa, Jharkhand, small part of GWB, SHWB, Western assam and Meghalaya , central Arunachal Pradesh and east NMMT.

The CC between HEM and IMD is less significant than IMR, mostly negative correlation is seen in small parts of Punjab, Haryana and Himachal Pradesh, Eastern West Rajasthan, East Rajasthan, West MP, Sourashtra, Parts of Gujarat, northern part of Konkan, Western Madhya Maharashtra, south Marathwada, NI Karnataka, Kerala, parts of Tamil Nadu, south costal AP, south Telangana central costal AP, costal parts of Orrisa, Jharkhand, small part of GWB, SHWB, Western Assam and Meghalaya , central Arunachal Pradesh, east and south NMMT. Areas significantly correlated are Vidarbha, Telangana, East Assam and Meghalaya, Parts of east and west UP, Haryana and Rajasthan, J&K.

During July 2022 the correlation coefficient between IMR and IMD is low in South J&K, Parts Himachal Pradesh, central Uttarakhand, West Punjab, Parts of West Rajasthan, Central East Rajasthan, north Saurashtra, Gujarat region, Konkan, Coastal Karnataka, SI Karnataka, Kerala, Parts Tamil Nadu, Rayalaseema, North Orrisa, Parts of Arunachal Pradesh, central Assam & Meghalaya, NMMT. At the same time, it shows positive

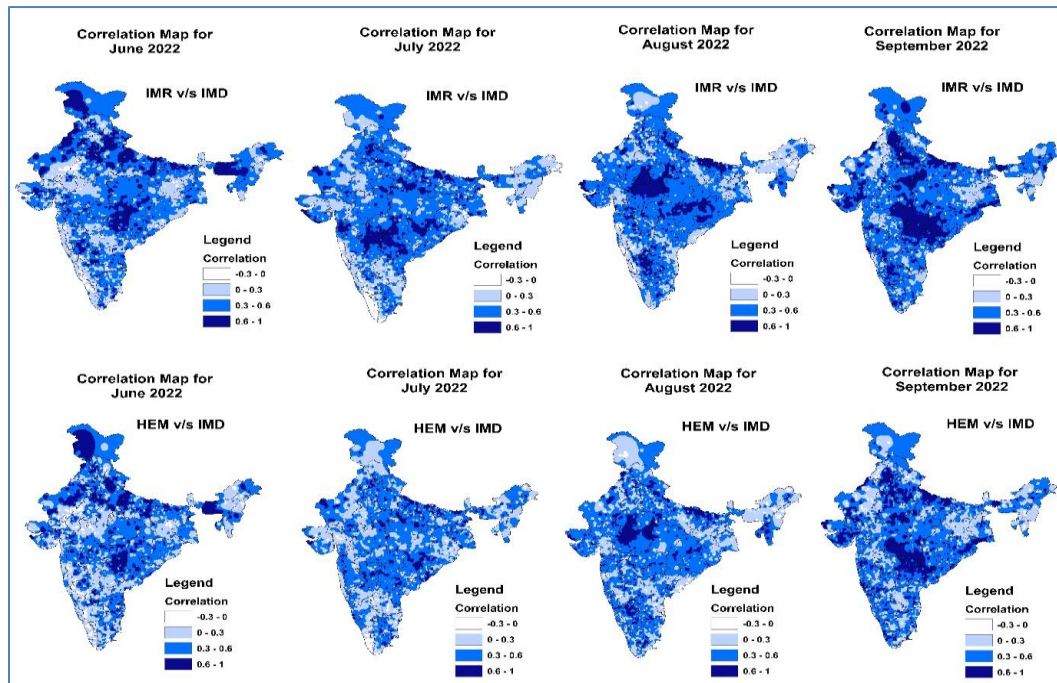


Fig. 6. Correlation plots 2022

correlations in parts of Haryana, the Western part of west Rajasthan, South Saurashtra, North Konkan and adjoining Madhya Maharashtra, Marathwada, Telangana, Central Vidarbha, Central Chhattisgarh and adjoining Orissa, Major parts of East UP, Scattered parts of Bihar.

The CC between HEM and IMD is negative in Central J&K, Himachal Pradesh, Parts of Uttarakhand, east of western UP, West Punjab, Eastern parts of West Rajasthan, Central East Rajasthan, Parts of east and west MP, north Saurashtra, Gujarat region, South Konkan, Central Madhya Maharashtra, NI Karnataka, SI Karnataka, Kerala, Parts Tamil Nadu, Rayalaseema, North Orissa and adjoining Jharkhand, Scattered parts of Bihar, North SHWB, Parts of Arunachal Pradesh, central Assam & Meghalaya, NMMT. Whereas it's high in parts of Haryana, the Western part of west Rajasthan, parts of Marathwada and Telangana, east Chhattisgarh and adjoining Orissa, North Coastal AP, Major parts of East UP, Scattered parts of Bihar.

During August 2022 the correlation coefficient between IMR and IMD is insignificant in central J&K, Parts of Punjab and Haryana, South of east UP, Parts of West Rajasthan, Northern East Rajasthan, Gujarat region, South Konkan and adjoining Madhya Maharashtra, Costal Karnataka, NI Karnataka, Kerala, Parts Tamil Nadu and Telangana, Costal AP, Jharkhand and scattered parts of GWB, Arunachal Pradesh, Assam & Meghalaya, north NMMT. It is significant in parts of Punjab, Uttarakhand, West Saurashtra, Eastern East Rajasthan, West MP and

adjoining East MP, parts of Madhya Maharashtra and SI Karnataka, east Vidarbha, Central Chhattisgarh and adjoining Orissa, Northern parts of East UP, North Bihar.

The CC between HEM and IMD is poor in West J&K, Parts of Himachal Pradesh, Parts of Punjab and Haryana, Scattered parts of West Rajasthan, Central East Rajasthan, Gujarat region, central Konkan and adjoining Madhya Maharashtra, Parts of Marathwada, NI Karnataka, south Kerala, Parts Tamil Nadu, costal Ap and adjoining Rayalaseema, South Telangana, North Orissa, Jharkhand, GWB, North SHWB, Arunachal Pradesh, Assam & Meghalaya, North NMMT. Better performance can be observed in parts of Haryana and Uttarakhand, east Rajasthan, West MP and adjoining east MP, parts of east UP and North Bihar, SI Karnataka, Parts of Tamil Nadu, central Chhattisgarh and adjoining Orissa, South NMMT.

During September 2022 the correlation coefficient between IMR and IMD is poor in central J&K, West Punjab, Uttarakhand, West Rajasthan, Scattered parts of East Rajasthan, Gujarat region, central Madhya Maharashtra, South Konkan and adjoining Costal Karnataka, east NI Karnataka, Parts Tamil Nadu and Rayalaseema, Jharkhand and scattered parts of Bihar, central Arunachal Pradesh, south NMMT. It is positive in central J&K, east Punjab, Haryana, west UP, northern east UP, south Saurashtra, West MP and adjoining East MP, SI Karnataka, Telangana, Vidarbha, south Chhattisgarh, north Orissa, East SHWB.

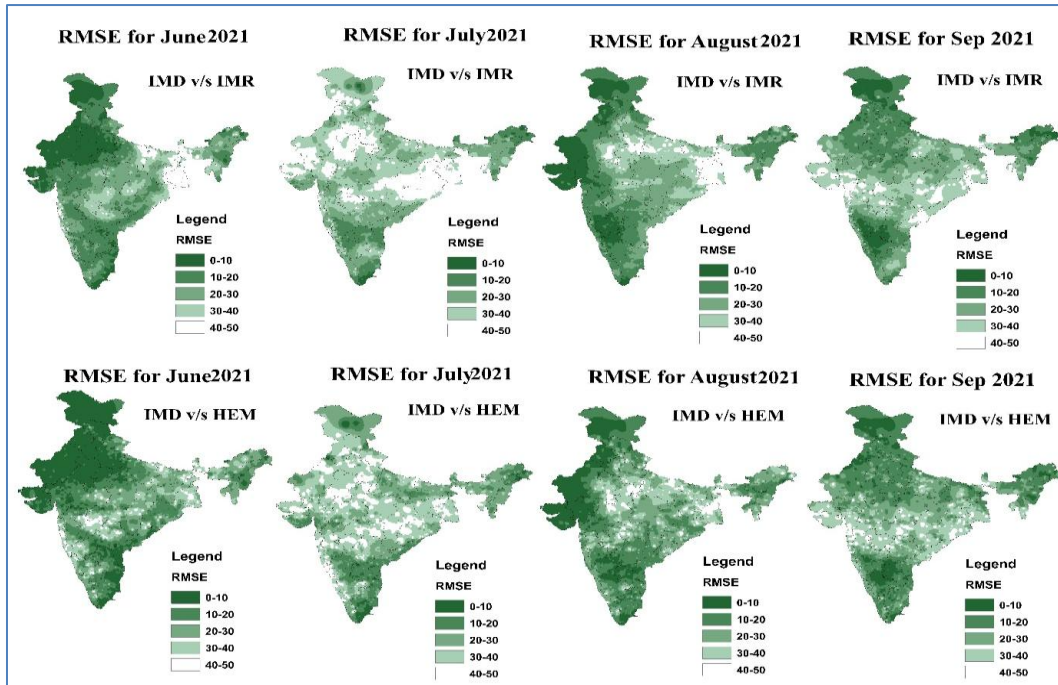


Fig. 7 RMSE plots 2021

The CC between HEM and IMD is negative in West J&K, Parts of Himachal Pradesh, west Punjab, Uttarakhand, west Rajasthan & adjoining East Rajasthan, scattered parts of Madhya Maharashtra and Marathwada, SI Karnataka, Parts Tamil Nadu, Rayalaseema, Jharkhand, parts of GWB, parts of Bihar, North SHWB, Arunachal Pradesh, parts of Assam & Meghalaya, NMMT. Positive cc can be seen in east Punjab, Parts of Haryana and west UP, North of east Rajasthan, West MP, parts of east UP, Saurashtra, south Konkan, north Telangana, Vidarbha, north Orissa, east SHWB.

3.3. RMSE

To highlight regions where the satellite estimates deviate more from the actual rainfall measured by rain gauges RMSE plots are generated. This allows to check the regional strengths and weakness of the estimated products. Fig. (7) shows the RMSE value between IMR-IMD and HEM-IMD for the monsoon months of 2021.

During June 2021 RMSE for IMR has outstanding accuracy throughout the country except for Konkan, Marathwada and Adjoining parts of Vidarbha, North Telangana, central Chhattisgarh, Bihar, eastern east UP and adjoining west UP, eastern Jharkhand, GWB, SHWB.

On the other hand, HEM show comparable performance to IMR and areas with high RMSE include East Uttarakhand, Konkan, NI Karnataka, Parts of SI

Karnataka, south of west MP, Marathwada and Adjoining parts of Vidarbha, North Telangana, Chhattisgarh, Jharkhand, GWB, SHWB.

During July 2021 RMSE for IMR is very poor over wide parts of the country the country except for South J&K and adjoining Himachal Pradesh, North Punjab, Haryana, West UP, Parts of west Rajasthan, East Rajasthan, north Saurashtra and Gujarat region, scattered parts of Konkan, North Marathwada and adjoining Madhya Maharashtra, Central Chhattisgarh and adjoining West MP, Orrisa, Jharkhand, south Bihar, GWB. Poor RMSE can be observed in North J&K, east Himachal Pradesh, South Saurashtra and Gujarat, NI&SI Karnataka, South Tamil Nadu, Rayalaseema, south Costal AP, Arunachal Pradesh, SHWB, Parts of NMMT.

HEM performance in this month is also poor where East Punjab, North Haryana, south Uttarakhand, West UP, Parts of west Rajasthan, East Rajasthan, north Saurashtra and Gujarat region, Northern pockets of East and West MP, Konkan, Costal Karnataka, scattered parts of Madhya Maharashtra, central Marathwada and adjoining Telangana, Vidarbha, Central Chhattisgarh and adjoining Orrisa, West Jharkhand and adjoining GWB show better results and north J&K, east Himachal Pradesh, Eastern UP and adjoining Bihar, West Punjab, and Rajasthan, South Saurashtra and Gujarat, North Madhya Maharashtra, NI&SI Karnataka, Tamil Nadu, Rayalaseema, Coastal AP, Arunachal Pradesh, SHWB, eastern Arunachal Pradesh have insignificant RMSE.

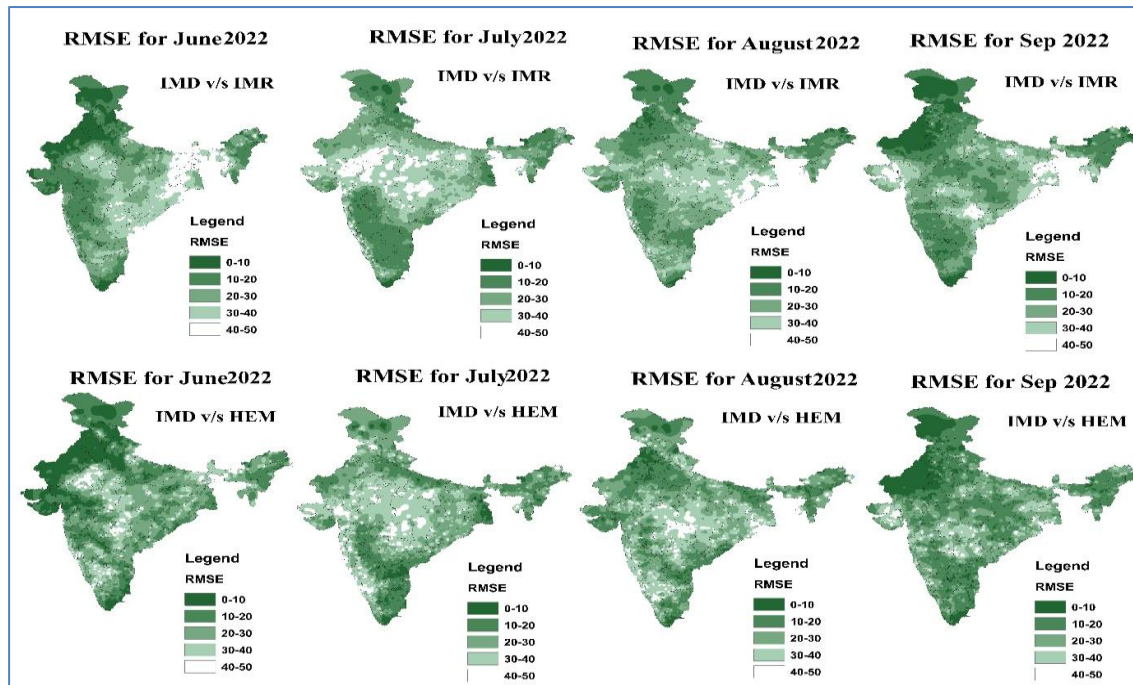


Fig. 8. RMSE plots 2022

During August 2021, RMSE for IMR is overall excellent, which can be seen in eastern east Rajasthan, south of west UP and adjoining MP, East UP, parts of Bihar, Jharkhand, GWB, parts of Orissa, Vidarbha and adjoining MP. Poor performance is observed in J&K, Himachal Pradesh, Uttarakhand, Punjab, West Rajasthan, Saurashtra, Gujarat, Madhya Maharashtra, NI&SI Karnataka, South Tamil Nadu, West Rayalaseema, Arunachal Pradesh, Assam, and Meghalaya, NMMT.

HEM performance is above average and good RMSE is in eastern east Rajasthan, west UP, West MP, East UP, cattered parts of Bihar, Jharkhand, GWB, parts of Orissa and Jharkhand, SHWB, Vidarbha Scattered parts of Marathwada and Kerala. Areas with low RMSE include J&K, Himachal Pradesh, parts of Uttarakhand, Punjab, West Rajasthan, parts of Haryana, Saurashtra, Gujarat, NI&SI Karnataka, South Tamil Nadu, Rayalaseema, south Costal AP, North Orissa, Assam, and Meghalaya.

During September 2021, IMR shows the significant performance of RMSE in parts of West Rajasthan, East west UP, Saurashtra, Gujarat region, Konkan, Madhya Maharashtra, Marathwada, west Vidarbha, central Chhattisgarh, Costal AP, east Jharkhand, GWB, Orissa, central SHWB, south NMMT. Low RMSE is observed in J&K, Himachal Pradesh, Uttarakhand, Punjab, Haryana, West UP, NI&SI Karnataka, South Tamil Nadu, West Rayalaseema, Arunachal Pradesh, Assam and Meghalaya, NMMT.

HEM performance is significant in the south of west and east Rajasthan, Gujarat region, Konkan, Madhya Maharashtra, Marathwada, east Telangana, Vidarbha, central Chhattisgarh, north Coastal AP, parts of Jharkhand, central Bihar, GWB, Orissa, central SHWB, south NMMT. Poor results are seen in J&K, Himachal Pradesh, Uttarakhand, Punjab, north of West and east Rajasthan, Haryana, west UP, north Gujarat, NI&SI Karnataka, South Tamil Nadu, Rayalaseema, south Costal AP, North GWB, Arunachal Pradesh, central, NMMT.

Fig. (8) shows the RMSE value between IMR-IMD and HEM-IMD for monsoon months of 2021. The range of value is 0 to 50.

During June 2022 IMR show significant performance of RMSE in East Rajasthan and adjoining west MP, scattered parts of Konkan, North Telangana, south Vidarbha, Coastal AP, Orissa, Jharkhand, Bihar, west GWB, SHWB, west Assam and Meghalaya. Areas with low RMSE are seen in J&K, Himachal Pradesh, Uttarakhand, West UP, Punjab, Haryana, west Rajasthan, west Saurashtra, Gujarat and adjoining west MP, Madhya Maharashtra, South Tamil Nadu, Parts of Arunachal Pradesh, NMMT.

HEM show better accuracy in West Himachal Pradesh, eastern part of West UP, east Rajasthan, West MP, south Konkan, Costal Karnataka, north Kerala, SI Karnataka, Telangana, Vidarbha, east Bihar, SHWB, west

Assam and Meghalaya. Whereas low accuracy is seen in North J&K, east Himachal Pradesh, Haryana, Punjab, west Rajasthan, West UP, Saurashtra and Gujarat, Madhya Maharashtra, East NI Karnataka, coastal Tamil Nadu, east GWB, eastern Arunachal Pradesh.

During July 2022, IMR's overall performance was below average, but areas with high accuracy of RMSE are south of west and east UP, East Rajasthan, north Saurashtra, Gujarat region, West and East MP, Vidarbha, scattered parts of Konkan and Coastal Karnataka, North Telangana Chhattisgarh, central Bihar. However, less accuracy is in J&K, Himachal Pradesh, Uttarakhand, South Saurashtra, Madhya Maharashtra, Marathwada, NI&SI Karnataka, South Kerala, Tamil Nadu, Rayalaseema, south Coastal AP, east GWB, Arunachal Pradesh, SHWB, Parts of Assam and Meghalaya, NMMT.

HEM performance is fair overall with areas of high RMSE accuracy are West Himachal Pradesh, Parts of Uttarakhand, east UP, East Rajasthan, north Saurashtra, Gujarat region, East and West MP, Konkan and adjoining Madhya Maharashtra, Coastal Karnataka, SI Karnataka, north Telangana, Vidarbha, Central Chhattisgarh, parts of Orissa and Jharkhand. Low RMSE accuracy is observed in North J&K, east Himachal Pradesh, north of East and west UP, east Haryana, West Rajasthan, South Saurashtra, East Madhya Maharashtra and adjoining Marathwada, NI Karnataka, Tamil Nadu, Rayalaseema, Coastal AP, GWB, Arunachal Pradesh, SHWB, NMMT.

During August 2022, IMR's overall performance is below average, but areas with high accuracy of RMSE are Gujarat region, parts of Konkan, coastal Karnataka, Vidarbha, central West MP, east of east UP and adjoining Bihar, Chhattisgarh, Orissa, GWB and adjoining Jharkhand. Low RMSE accuracy is in J&K, Himachal Pradesh, Uttarakhand, Punjab, West Rajasthan, Haryana, Saurashtra, Madhya Maharashtra, NI Karnataka, South Tamil Nadu, Rayalaseema, Coastal AP, Bihar, SHWB, Arunachal Pradesh, Assam and Meghalaya.

HEM shows high RMSE in parts of Himachal Pradesh, Uttarakhand, southern West Rajasthan, East UP, West, and east MP, parts of Konkan, coastal Karnataka, Vidarbha, SI Karnataka, south Bihar, Jharkhand, GWB, parts of Orissa and Jharkhand, Scattered parts of NMMT. Whereas low RMSE accuracy is in J&K, parts of Himachal Pradesh, west UP, Punjab, West Rajasthan, Haryana, Saurashtra and adjoining Gujarat, Tamil Nadu, Rayalaseema, Coastal AP, east Bihar, Assam and Meghalaya.

During September 2022, High RMSE accuracy is in parts of East UP, Saurashtra, Gujarat region, Telangana,

Vidarbha, Coastal Orissa, GWB and adjoining Jharkhand, central SHWB, south NMMT. poor accuracy of RMSE is in J&K, Himachal Pradesh, Uttarakhand, Punjab, Haryana, East and west Rajasthan, West UP, NI&SI Karnataka, South Tamil Nadu, and Kerala, Rayalaseema, central Chhattisgarh, Arunachal Pradesh, Assam, and Meghalaya, north NMMT.

HEM performance is excellent for RMSE accuracy in parts of Uttarakhand, Saurashtra, Gujarat region, Konkan, Coastal Karnataka, Madhya Maharashtra, parts of Marathwada, Telangana, Vidarbha, parts of Jharkhand and Orissa, west GWB. Low RMSE accuracy is in J&K, Himachal Pradesh, Uttarakhand, Punjab, Haryana, East and west Rajasthan, NI&SI Karnataka, Kerala, Tamil Nadu, Rayalaseema, south Coastal AP, central Chhattisgarh, parts of Orissa, west Arunachal Pradesh, Assam and Meghalaya, NMMT.

3.4. Bias map

The BIAS score measures the ratio of the frequency of estimated rain area to the frequency of observed rain areas. Indicates whether the estimation system tends to underestimate or overestimate events. Does not measure how well the estimation corresponds to the observations, only measures relative frequencies. Bias map of 2021 and 2022 is shown in Figs. (9&10) which shows bias from monthly average rainfall in each sub division. A bias analysis assesses the average difference between the satellite estimation and the gauge precipitation amount. A bias value greater than 10 indicates an underestimation and values above -10 showing overestimation. The values between +10 and -10 are considered accurately estimated.

In June 2021, both the IMR and HEM rainfall products showed a slight underestimation in the northern and western parts of India, including Jammu & Kashmir, Himachal Pradesh, Punjab, Uttarakhand, and regions like East and West Rajasthan, Gujarat, Saurashtra, and Konkan Goa. Notably, IMR is uniquely underestimated in Kerala and coastal Karnataka. IMR and HEM were also underestimated in Assam and Meghalaya, while IMR specifically showed underestimation in Arunachal Pradesh.

The IMR product exhibited high overestimation in Gangetic West Bengal and moderate overestimation in June in Bihar, Jharkhand, Odisha, Telangana, Vidarbha, and western Madhya Pradesh. Conversely, HEM showed slight underestimation in Sub-Himalayan West Bengal, Vidarbha, and Marathwada regions. The rest of the regions showed varying performances between IMR and HEM.

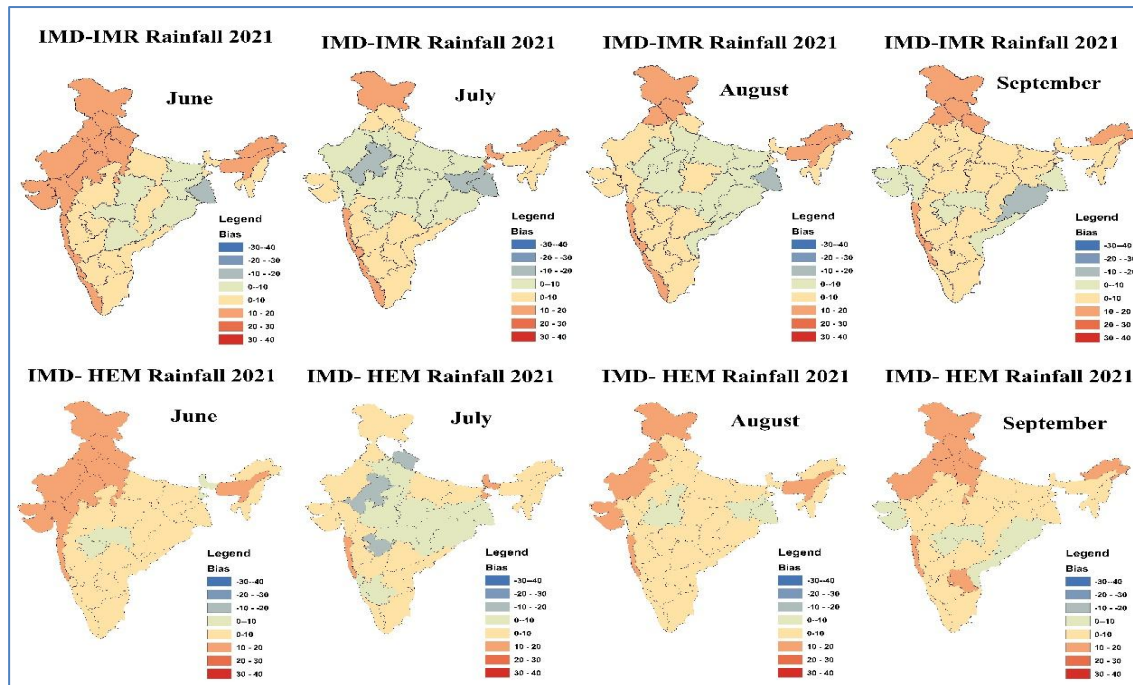


Fig. 9. Bias map 2021

IMR continued to underestimate Jammu & Kashmir, Sub-Himalayan West Bengal, the western coast, and Arunachal Pradesh in July. Conversely, HEM overestimated Sub-Himalayan West Bengal, Uttarakhand, and Konkan Goa rainfall. IMR showed high underestimation in East Rajasthan, Jharkhand, and Gangetic West Bengal, with a slight overestimation in central India. HEM was overestimated in East Rajasthan, Marathwada, and Uttarakhand, with slight overestimation in coastal and southern interior Karnataka and a significant portion of central India.

In August, IMR showed underestimation in Jammu & Kashmir, Himachal Pradesh, Punjab, the western coast, and the northeastern states, while overestimating in Gangetic West Bengal and slightly overestimating in central India, excluding western Madhya Pradesh. HEM was underestimated in Jammu & Kashmir, Punjab, West Rajasthan, Konkan Goa, Assam, and Meghalaya and overestimated in western Madhya Pradesh, Jharkhand, and Gangetic West Bengal.

During September, both IMR and HEM showed similar bias patterns. IMR underestimated in Jammu & Kashmir, Himachal Pradesh, Punjab, Uttarakhand, Arunachal Pradesh, and Konkan Goa, while overestimating significantly in Odisha and slightly in Saurashtra, Gujarat, Marathwada, Vidarbha, Gangetic West Bengal, and coastal Andhra Pradesh. HEM showed underestimation in Jammu & Kashmir, Himachal Pradesh, Punjab, Uttarakhand, West Rajasthan, Konkan,

Royalaseema, and Arunachal Pradesh, with overestimation in Saurashtra, Marathwada, Vidarbha, Odisha, and coastal Andhra Pradesh.

Overall, the maps indicate that IMR generally overestimated rainfall in the central and eastern parts of the country, while it underestimated mainly in the northern regions, including the Himalayas, the western coast, and parts of the northeastern states. HEM, on the other hand, tended to underestimate rainfall in the northern and northwestern regions, the Konkan coast, and parts of the northeastern states while overestimating in a few regions such as Haryana, East Rajasthan, central Madhya Pradesh, and the eastern part of the country.

During June 2022 (Fig. 10), both IMR and HEM showed similar underestimation patterns in regions such as Jammu & Kashmir, Konkan, and Arunachal Pradesh. However, IMR is uniquely underestimated in the NMMT region. IMR displayed high overestimation in Sub-Himalayan West Bengal (SHWB) and slight overestimation in Jharkhand, Odisha, Telangana, southern interior Karnataka, Vidarbha, and eastern Madhya Pradesh. HEM also showed overestimation, predominantly in the eastern parts of India, with a notably higher overestimation in SHWB.

In July 2022, IMR demonstrated underestimation in Jammu & Kashmir, Gujarat, and Saurashtra. Conversely, HEM observed high underestimation in Konkan and slight

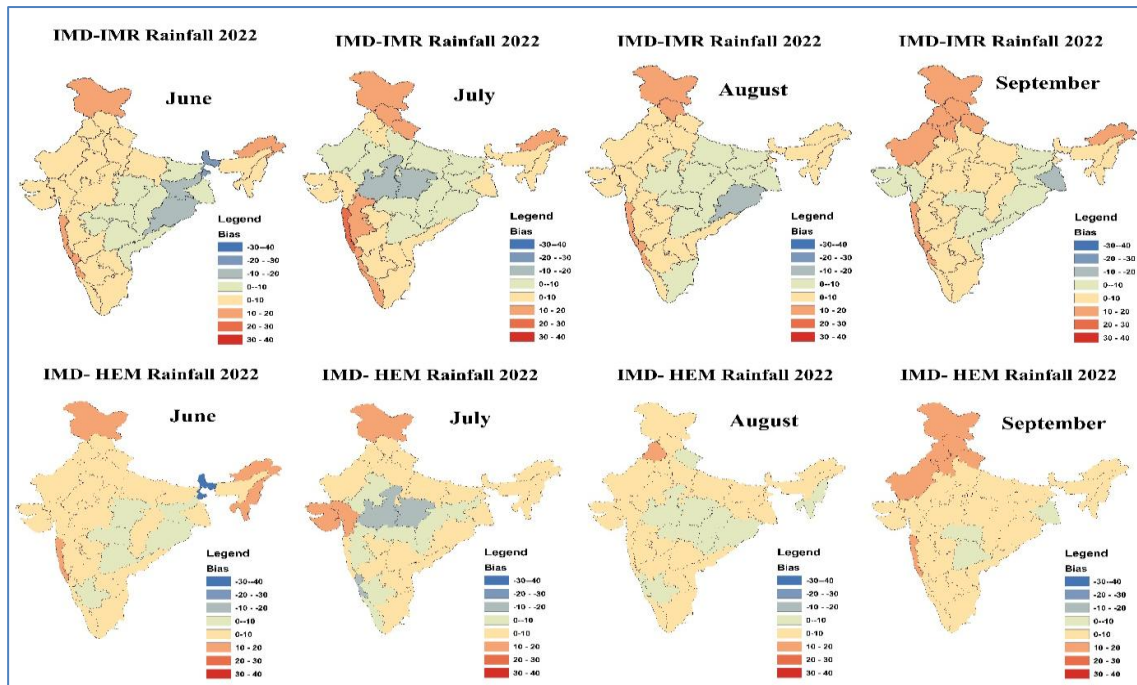


Fig. 10. Bias map 2022

underestimation in Jammu & Kashmir, Uttarakhand, Himachal Pradesh, Arunachal Pradesh, Madhya Maharashtra, coastal Karnataka, and Kerala. Both IMR and HEM showed high overestimation in West and East Madhya Pradesh. Additionally, IMR exhibited overestimation in East Rajasthan, Madhya Maharashtra, Karnataka, Kerala, Jharkhand, Chhattisgarh, and Vidarbha. HEM, however, showed overestimation across central India, including Telangana.

In August 2022, IMR showed high underestimation only in Punjab, whereas HEM showed underestimation in Jammu & Kashmir, Himachal Pradesh, Konkan, and coastal Karnataka. IMR displayed overestimation in Karnataka, coastal Karnataka, Uttarakhand, and central India. HEM demonstrated overestimation in central and eastern India, as well as in Tamil Nadu.

During September 2022, both IMR and HEM exhibited similar underestimation in Jammu & Kashmir, Punjab, Himachal Pradesh, Uttarakhand, Haryana, and West Rajasthan, with HEM uniquely underestimating in Arunachal Pradesh. IMR showed overestimation in Telangana, Vidarbha, and Gangetic West Bengal, which was also common in HEM. Additionally, HEM was overestimated in Saurashtra, Gujarat, the eastern part of India, Telangana, and Vidarbha.

Overall results show that, in 2021 and 2022, IMR and HEM demonstrated underestimation patterns in the

northern regions, including Jammu & Kashmir and Himachal Pradesh. Overestimation was common across both years in central and eastern India, particularly in regions such as SHWB, Telangana, and Vidarbha. Both years also saw consistent underestimation by IMR in the western coast and certain northeastern states. At the same time, HEM similarly underestimated in the northern and northwestern regions and parts of the northeastern states. This consistent pattern of bias highlights the areas where improvements in rainfall estimation methods are crucial.

4. Conclusions

This research investigates the correlation and accuracy between satellite-derived rainfall estimates (IMR and HEM) and ground-based measurements (IMD) over India during the monsoon seasons of 2021 and 2022. The study focuses on various metrics, including correlation coefficients, root mean square error (RMSE), and bias scores, to evaluate the performance of these satellite products in capturing daily rainfall patterns.

The analysis revealed that the correlation between IMR and IMD was generally positive across the country, with regional variations in strength. In contrast, HEM showed a lower correlation with IMD but still provided useful data. Significant correlations were observed in central and western India for both IMR and HEM during the monsoon months of 2021 and 2022, with some exceptions in the Himalayan and northeastern states.

RMSE analysis revealed that IMR and HEM had varying degrees of accuracy, with IMR generally showing better performance. Regions such as central and western India exhibited lower RMSE values, indicating higher accuracy, while higher RMSE values were noted in the Himalayan region and parts of southern India. Bias maps indicated that IMR and HEM tended to underestimate rainfall in the northern and western parts of India and overestimate in regions like Gangetic West Bengal and central India. The degree of underestimation and overestimation varied between the two satellite products, with IMR often showing a slight underestimation in more regions than HEM. It is important to mention that the observed regional variation in performance metrics such as RMSE and correlation is partly influenced by the density and distribution of ground-based observation stations, which limits validation in data-sparse areas.

The study underscores the importance of continuously validating and improving satellite-derived rainfall estimates for better weather prediction and water resource management. The findings highlight the regional differences in the performance of these satellite products, emphasizing the need for localized calibration to improve their accuracy further. This research provides practical value for multiple end users. For meteorological agencies, it strengthens the case for using satellite rainfall estimates in real-time forecasting, especially in data-scarce regions. Disaster management authorities can benefit from improved spatial rainfall monitoring to support early warning systems for floods and landslides. In the agricultural sector, reliable rainfall estimation during the monsoon season is critical for irrigation planning, crop forecasting, and risk mitigation. By identifying the strengths and weaknesses of INSAT-based products regionally, this study supports informed decision-making and prioritization for localized calibration or ground network improvements. Future research should focus on extending the analysis to include more years and additional satellite products, investigating the underlying causes of discrepancies in satellite and ground-based measurements, and developing advanced algorithms for more accurate rainfall estimation, particularly in challenging terrains like the Himalayas and coastal regions. By enhancing the accuracy of satellite-derived rainfall estimates, we can significantly improve rainfall monitoring capabilities, ultimately aiding in disaster management and agricultural planning in India.

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Authors' Contributions

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Annexure 1

Subdivisions and Abbreviations

Arunachal	ARUPR
Bihar	BHR
Chhattisgarh	CHTGH
Coastal Andhra Pradesh	CAP
Coastal Karnataka	CK
Orissa	ORS
Gujarat	GUJ
Gangetic west Bengal	GWB
Haryana	HARY
Delhi	DLH
Himachal Pradesh	HP
Jammu and Kashmir	J&K
Jharkhand	JHRKND
Kerala	KER
Konkan	KKN
Lakshadweep	LKSDP
Madhya Maharashtra	MM
Nagaland, Manipur, Mizoram, Tripura	NMMT
Madhya Pradesh	MP
Marathwada	MRTHWD
North interior Karnataka	NIK
Punjab	PJB
Rajasthan	RAJ
Rayalaseema	RYLSM
Saurashtra & Kutch	SAU
Sub Himalayan West Bengal	SHWB
South Interior Karnataka	SIK
Sikkim	SKM
Telangana	TLNGN
Tamil Nadu	TN
Tripura	TRP
Uttar Pradesh	UP
Uttarakhand	UTRKND
Vidarbha	VID
Sub Himalayan West Bengal	SHWB
Gangetic West Bengal	GWB