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Evaluation of INSAT-3DR Hydro-Estimator product for monsoon season rainfall at block-level and its utility in forecast verification: A case study in Karnal district, India

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सार – INSAT-3D आर्द्र INSAT-3DR मौसम उपग्रह डेटासेट की उपलब्धता आर्द्र आमेलन ने मध्यम अवधि के मौसम पूर्वानुमानों की सटीकता में सुधार किया है। परंपरागत रूप से, पूर्वानुमान को यथास्थान प्रेक्षणों के आधार पर सत्यापित किया जाता है। हालाँकि, यथास्थान वेधशालाओं का वितरण कई कारणों से एक समान नहीं है, जैसे रहने योग्य स्थिति, पहाड़ी भूभाग, प्रचालनात्मक लागत आदि।रखरखाव आर्द्रप्रचालनात्मक मुद्दों के कारण स्वचालित मौसम स्टेशनों से हर समय डेटा की उपलब्धता की भी गारंटी नहीं है। इसलिए, यथास्थान डेटा के अभाव में पूर्वानुमान को सत्यापित करना बहुत मुश्किल हो जाता है।वर्तमान अध्ययन में, 2020 आर्द्र 2021 के दक्षिण-पश्चिमी मॉनसून ऋतु के लिए यथास्थान वर्षामापी डेटा का उपयोग करके आसंध (एएस), घरौंदा (जीडी), इंद्री (आईडी), करनाल (केए), नीलोखेड़ी (एनके) ब्लॉकों के लिए कौशल स्कोर विश्लेषण करके मूल्यवर्धित वर्षा पूर्वानुमान के कौशल का आकलन किया जाता है। मुनक (एमयू), कुंजपुरा (केजे) आर्द्र निसिंग (एनआई) ब्लॉकों के लिए वर्षामापी डेटा उपलब्ध नहीं है। इस अंतर को कम करने के लिए, वर्तमान अध्ययन में, आईएमडी द्वारा जारी ब्लॉक-स्तरीय वर्षा पूर्वानुमान को INSAT-3DR उपग्रह हाइड्रो-एस्टीमेटर (HE) वर्षा उत्पाद का उपयोग करके सत्यापित किया जाता है। दृष्टिकोण में विश्वास हासिल करने के लिए, INSAT-3DR व्युत्पन्न HE वर्षा अनुमान को करनाल जिले में उपलब्ध वर्षा-मापकों की तुलना में मान्य किया गया है। अध्ययन से पता चलता है कि उपग्रह से प्राप्त वर्षा डेटा का उपयोग ब्लॉक स्तर पर दैनिक वर्षा के बेहतर पूर्वानुमान आर्द्र कृषि मौसम परामर्श बुलेटिन तैयार करने के लिए किया जा सकता है। मौसम प्राचलों के पूर्वानुमान की सटीकता पहले से ही किसानों के लिए कृषि मौसम परामर्श बुलेटिन (एएबी) की तैयारी के रूप में उचित क्षेत्र संचालन आर्द्र फसल प्रबंधन प्रथाओं के लिए उपयोगी पाई जाती है।

ABSTRACT. The availability and assimilation of INSAT-3D and INSAT-3DR weather satellite datasets have improved the accuracy of medium-range weather forecasts. Conventionally, the forecast is verified against the in-situ observations. However, the distribution of in-situ observatories is not uniform for many reasons like, in-habitable conditions, mountain terrains, operational cost *etc*. The availability of data from Automatic weather stations is also not guaranteed at all times because of maintenance and operational issues. Therefore, in the absence of in-situ data it becomes very difficult to verify the forecast. In the current study, the skill of value-added rainfall forecast is assessed by carrying out skill score analysis for Assandh (AS), Gharaunda (GD), Indri (ID), Karnal (KA), Nilokheri (NK) blocks using in-situ rain-gauge data for the southwest monsoon season of 2020 and 2021. For the Munak (MU), Kunjpura (KJ) and Nissing (NI) blocks, the data from rain-gauges are not available. In order to fill this gap, in the present study, the block-level value-added rainfall forecast issued by IMD, is verified by utilizing INSAT-3DR satellite Hydro-estimator (HE) rainfall product. In order to gain confidence in the approach, the INSAT-3DR derived HE rainfall estimate is validated against the available rain-gauges in Karnal district. The study revealed that the rainfall data received from the satellite can be used for better forecasting of daily rainfall at the block level and preparation of gromet advisory bulletin. The accuracy of the forecast of weather parameters in advance is found to be useful for farmers for doing appropriate field operations and crop management practices in the form of preparation of Agromet Advisories Bulletin (AAB).

Key words– Rainfall forecast, Verification, Insat-3DR, Hydro-Estimator

1. Introduction

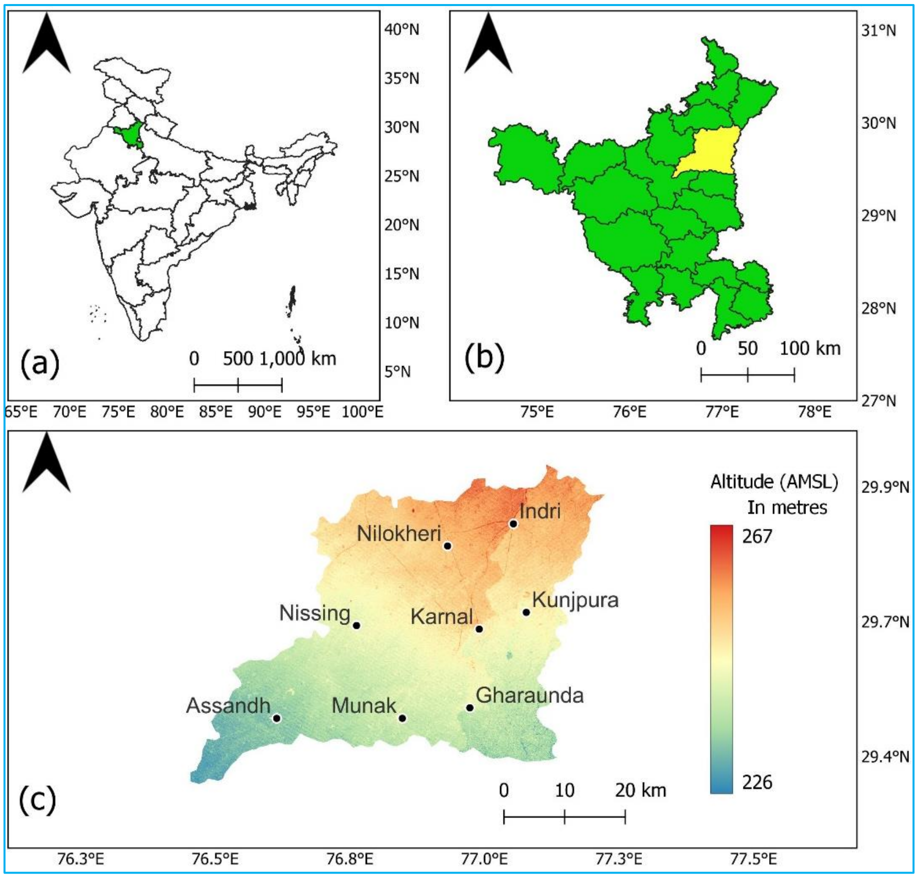
Rainfall forecasting is an essential aspect of weather forecasting, as it has significant implications for various sectors, including agriculture, water management, and disaster preparedness. Accurate and reliable rainfall forecasts are critical in mitigating the adverse effects of extreme weather conditions, such as floods and droughts. In recent years, there have been significant advances in weather forecasting, including the development of sophisticated models and techniques for rainfall forecasting. However, the accuracy of rainfall forecasts is still subject to verification and validation (IMD-SOP, 2021). Verification and validation are essential aspects of any forecasting model or technique, as they provide a measure of the model's reliability and accuracy. Rainfall forecast verification practices involve comparing the forecasted rainfall amounts to the observed rainfall amounts to determine the accuracy of the forecasts. The use of weather observations for rainfall forecast verification is a common practice, and various methods have been developed to perform this task (Mitra *et al.*, 2013). Apart from using weather observations, attempts have also been made to verify rainfall forecasts using satellite or radar data. These techniques have the advantage of providing high-resolution rainfall data over a wide area, which can be useful in verifying large-scale forecasts. However, the use of satellite or radar data for rainfall forecast verification is still a developing field, and further research is needed to establish its effectiveness (Kumar and Varma, 2017).

The India Meteorological Department (IMD) issues block-level rainfall forecasts through its national network of observatories and weather stations. The IMD uses a combination of ground-based observations, satellite data, and computer models to forecast rainfall for each block in the country (IMD report, 2021). The IMD issues block-level rainfall forecasts on a weekly basis during the southwest monsoon season (June-September) and on a monthly basis during the post-monsoon and winter seasons (October-May). These forecasts are based on a statistical model that takes into account historical rainfall data, current weather conditions, and global climate patterns. The reliability and accuracy of medium-range weather forecasts were studied by several authors (Tripathi *et al.*, 2008; Lunagaria *et al.*, 2009; Chaudhari *et al.*, 2010; Mishra *et al.*, 2010; Sahu *et al.*, 2012) for different Agro-climatic zones of India.

The established practice for carrying out rainfall forecast verification involves the utilization of rain-gauge data as reference. For carrying out block level rainfall forecast verification, a dense rain-gauge network is required in every block of each district. But this is also a fact that, the distribution of manned rain-gauges is not uniform spatially. In remote areas and hilly terrains there are very few manned rain-gauges. On the other hand, the Automatic Weather Stations and Automatic Rain Gauges, operations are impacted due to maintenance issues. Therefore, operations and maintenance of a very dense rain-gauge network is a big challenge. At present such dense rain-gauge network are not present at pan-India scale in India. This observation gap can be filled by using remote sensing observations like Doppler weather Radar and Meteorological Satellites. Rainfall estimates from these remote sensing observations can be used for the verification of rainfall forecast over an area. The biggest advantage of remote sensing data is its near-real-time availability in all weather conditions. Therefore, in order to fill this gap, in this study a case study of both evaluation of satellite derived rainfall product with rain-gauges and the use of satellite derived rainfall product for rainfall forecast verification is presented. The Hydro-estimator (HE) rainfall product from INSAT-3DR is utilized in this study.

INSAT-3DR is an advanced meteorological satellite launched by the Indian Space Research Organization (ISRO) in 2016. It is equipped with state-of-the-art sensors and instruments that provide high-resolution images and data on atmospheric conditions, including temperature, humidity and rainfall. One of the key products derived from the INSAT-3DR satellite is the Hydro Estimator, which uses the infrared and visible channels of the satellite to estimate rainfall in real-time. The Hydro Estimator product is based on a technique that combines the brightness temperature data from the satellite with other meteorological data to estimate rainfall rates over a particular region (Kumar *et al.*, 2023).

The objective of this study is to demonstrate the use of satellite-derived rainfall estimates for the verification of rainfall forecasts. At present, the block-level weather forecast is issued by Meteorological Center Chandigarh, IMD for the Karnal district. The Karnal district has eight blocks namely Assandh (AS), Gharaunda (GD), Indri (ID), Karnal (KA), Nilokheri (NK), Munak (MU), Kunjpura (KJ) and Nissing (NI). Out of these eight blocks, the daily rainfall monitoring rain-gauge stations are available only in five blocks namely: AS, GD, ID, KA & NI. In the remaining three blocks; MU, KJ & NI, rain-gauge observations are not available. In the absence of rain-gauges, it becomes difficult for a forecaster to verify the issued forecast. Hence, the need arises for the use of remote sensing data for the verification of rainfall forecast, which is demonstrated in this study. This study focuses on analyzing rainfall data for each block to assess the accuracy of rainfall forecasts. By doing so, we can identify areas where forecasts are particularly reliable or



Figs. 1(a-c). Location of Study area (a-c). (c) Represents the altitude above mean see level of the Karnal district, along with the location of rain-gauges in the administrative blocks of Karnal district used in this study

unreliable and explore potential causes of these variations, such as topography or local weather patterns.

2. Study area

The Karnal District is located in the northern state of Haryana, India, and covers an area of approximately 1,968 square kilometers. The district is situated between 29.09° N and 29.5° N and 76.01° E and 76.42° E. It is surrounded by the districts of Panipat to the south, Kurukshetra to the west, Yamuna Nagar to the north and Uttar Pradesh state to the east (Fig. 1). The typical climate of this region is tropical and subtropical, semi-arid, with cold winters and warm, dry summers. The soils of Karnal district were loam and sandy loam with good depth, decent drainage, neutral to slightly alkaline pH, low in available Nitrogen (115-193 kg/ha) and Phosphorus (9-46 kg/ha) and medium in available Potassium (126-456 kg/ha). The district is predominantly rural, with agriculture being the primary occupation of the people. The major crops grown in the district include wheat, rice, sugarcane, and cotton. Karnal District is divided into eight administrative blocks, namely Assandh (AS), Gharaunda (GD), Indri (ID), Karnal (KA), Nilokheri (NK), Munak (MU), Kunjpura (KJ) and Nissing (NI)

3. Data used

3.1. *Gauge data*

Rainfall data from Daily Rainfall Monitoring Stations (DRMS) located in AS, GD, ID, KA & NI blocks of the Karnal district for the period of June-September, 2020 and 2021, is utilized to verify the rainfall forecast. This data was made available by Meteorological Center Chandigarh.

3.2. *Hydro estimator (HE) data*

INSAT-3DR is the third-generation Indian geostationary meteorological satellite, which was launched in September 2016. This advanced meteorological satellite carries a six-channel multi-spectral Imager payload. The Hydro-Estimator (HE) method (Varma and Gairola, 2015) is operational at the India Meteorological Department (IMD), under Multi-Mission Data Receiving and Processing System (MMDRPS), for retrieving precipitation from INSAT-3DR satellite observations. The applicability and reliability of H-E rain products from INSAT-3D/3DR are documented by various researchers (Kumar *et al*., 2021, Singh *et al*. 2018 a & b).

4. Methodology

4.1. *Forecast verification*

The forecasts are verified using ratio score, Hanssen and Kuipers (HK) Score, Probability of detection (POD), Heidke Skill Score (HSS), False alarm ratio (FAR), Critical Success Index (CSI) (Singh *et al*., 2005; Tripathi *et al*., 2008; Chauhan *et al*., 2008; Lunagaria *et al*., 2009; Chaudhari *et al*., 2010; Mishra *et al*., 2010; Sahu *et al*., 2012). The verification scores were calculated and have been used for verifying the rainfall and temperature forecasts as follows: In the following 2 × 2 contingency table, if 'Yes' stands for the occurrence of rain and 'No' stands for non-occurrence then

Observed	Forecast	
	Yes	No
Yes	True Positive (TP)	False Negative (FN)
No	False Positive (FP)	True Negative (TN)

The total number of cases (N) is given by: N = TP + FP + FN + TN

(*i*) Probability of Detection (POD): POD measures the proportion of observed events that were correctly forecasted. It is calculated as TP/(TP+FN).

(*ii*) False Alarm Ratio (FAR): FAR measures the proportion of non-events that were incorrectly forecasted as events. It is calculated as FP/(FP+TP).

(*iii*) Miss Rate: The miss rate measures the proportion of events that were not correctly forecasted. It is calculated as FN/(TP+FN).

(*iv*) Critical Success Index (CSI): CSI measures the proportion of correctly forecasted events out of the total number of events. It is calculated as TP/(TP+FN+FP).

(*v*) Heidke Skill Score (HSS): HSS measures the improvement of the forecast over random chance. It ranges from -1 to 1, with a score of 0 indicating no skill and a score of 1 indicating perfect skill. It is calculated as (TP+TNN)/(TP+TN+FP+FN-N), where N is the expected number of correct forecasts by chance.

(vi) Percentage Correct (PC): PC measures the proportion of correct forecasts out of the total number of forecasts. It is calculated as (TP+TN)/(TP+TN+FP+FN).

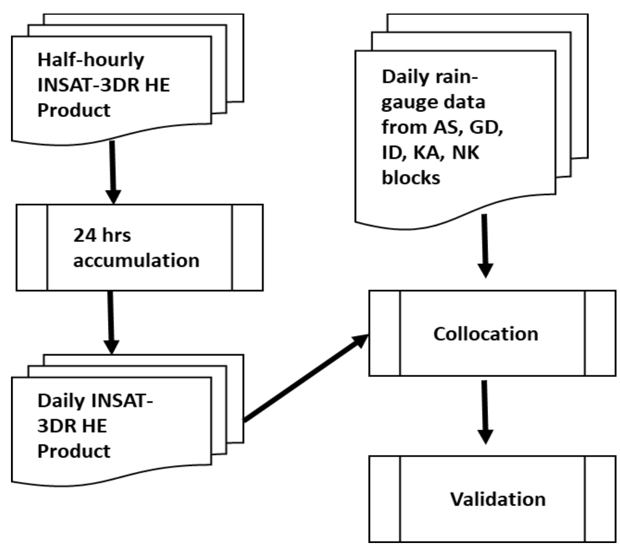
4.2. *Skill scores parameters for validation of INSAT-3DR HE product with rain-gauges*

The performance of the HE rainfall estimator is evaluated over AS, GD, ID, & KA blocks to increase the confidence for its use, for forecast verification.

(*i*) *Bias*: Bias measures the tendency of the forecast to over- or under-predict the observed values. It is calculated as the difference between the mean forecast and the mean observation.

(*ii*) *Correlation*: Correlation measures the linear relationship between the forecast and the observation. It ranges from -1 to 1, with a score of 0 indicating no correlation and a score of 1 indicating perfect positive correlation.

(*iii*) *Root Mean Square Error (RMSE)*: RMSE measures the difference between the forecast and the observation in the same units as the forecast. It is calculated as the square root of the average squared difference between the forecast and the observation.



Flowchart 1: Validation of INSAT-3DR derived Hydro Estimator (HE) rainfall product over the rain-gauges in Assandh (AS), Gharaunda (GD), Indri (ID), Karnal (KA), & Nilokheri (NK) blocks in Karnal district.

TABLE 1

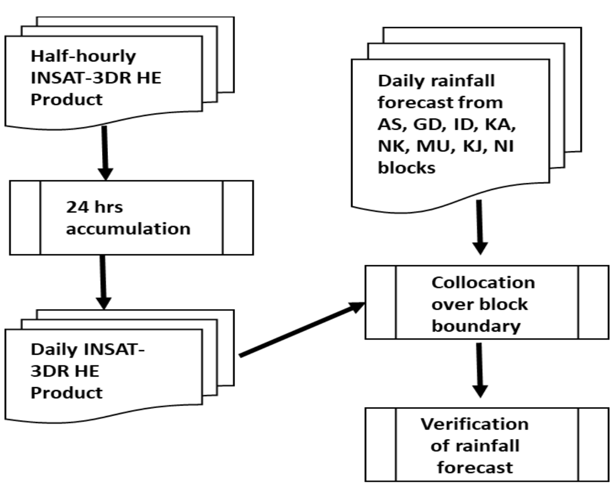
Verification of Rainfall Forecast for Monsoon season of 2021 (JJAS) for 05 blocks of Karnal District (2 × 2 contingency table)

Year	Blocks	Total no. of days	Successful forecasting (days)	Forecast failure (days)	Accuracy (%)	No. of Hits (days)	No. of False Alarms (days)	No. of misses (days)	No. of correct prediction of no rain (days)
JJAS, 2021	AS	122	77	44	63.63	21	36	8	54
	GD	122	73	48	60.33	22	39	9	51
	ID	122	74	47	61.15	28	43	4	46
	KA	122	72	49	59.4	29	39	10	43
	NK	122	79	42	65.28	29	34	8	50

TABLE 2

Skill Assessment of Rainfall Medium Range Forecast for Assandh, Gharaunda, Indri, Karnal, Nilokheri blocks over JJAS 2021 against rain-gauges

Year	Skill Score	Assandh	Gharaunda	Indri	Karnal	Nilokheri
JJAS, 2021	TS	0.32	0.31	0.37	0.37	0.41
	POD	0.72	0.71	0.87	0.74	0.78
	MISS	0.28	0.29	0.12	0.26	0.22
	FAR	0.40	0.43	0.48	0.48	0.40
	HSS	0.24	0.21	0.28	0.22	0.32
	PC	0.63	0.60	0.61	0.59	0.65



Flowchart 2: Verification of daily rainfall forecast over Assandh (AS), Gharaunda (GD), Indri (ID), Karnal (KA), Nilokheri (NK), Munak (MU), Kunjpura (KJ) &Nissing (NI) blocks in Karnal district using INSAT-3DR derived Hydro Estimator (HE) rainfall product.

5. Results

5.1. *Verification of Rainfall Forecast for AS, GD, ID, KA, NK Blocks for 2021 (JJAS)*

Table 1 shows the rainfall forecast verification accuracy and 2×2 contingency Table for JJAS of 2021. The highest accuracy for successful forecasting is achieved for NK block (79 days, *i.e.*, 65.28%) in 2021. The highest numbers of forecast failure days are observed over KA block (49 days). The overall forecast accuracy range for JJAS 2021 is from 59.4% to 65.28%. The skill score analysis based on the 2×2 contingency Table is discussed in following section.

5.2. *Skill Assessment of Rainfall Forecast for AS, GD, ID, KA, NK block sover JJAS 2021 against rain-gauges*

Based on the 2×2 contingency Table as shown in Table 1, the skill score analysis of the rainfall forecast is

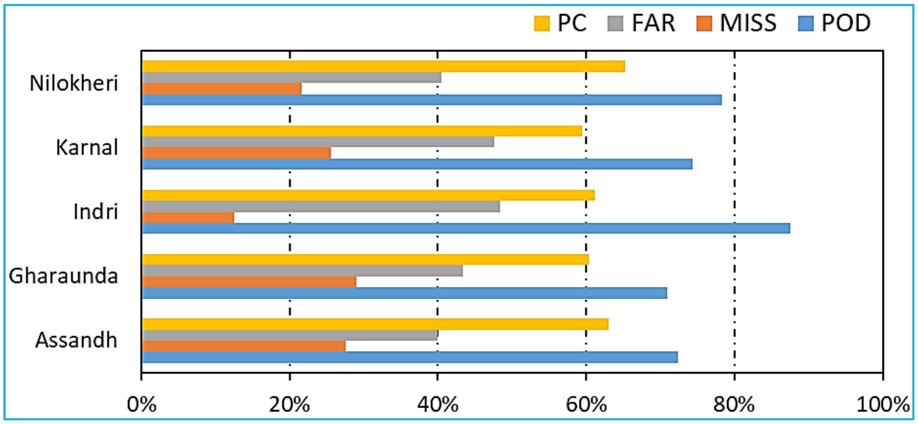


Fig. 2. Skill Assessment of Rainfall Forecast for AS, GD, ID, KA, NK blocks over JJAS 2021 against rain-gauges

TABLE 3

Verification of Satellite Rainfall using INSAT 3DR H-E, 2021 with IMD Rain-gauges

Skill Score	Assandh	Gharaunda	Indri	Karnal	Nilokheri
TS	0.46	0.51	0.57	0.53	0.55
POD	0.9	0.94	0.94	0.79	0.86
M	0.1	0.06	0.06	0.21	0.14
F	0.29	0.29	0.22	0.23	0.25
HSS	0.47	0.52	0.6	0.53	0.55
PC	0.75	0.77	0.82	0.78	0.79

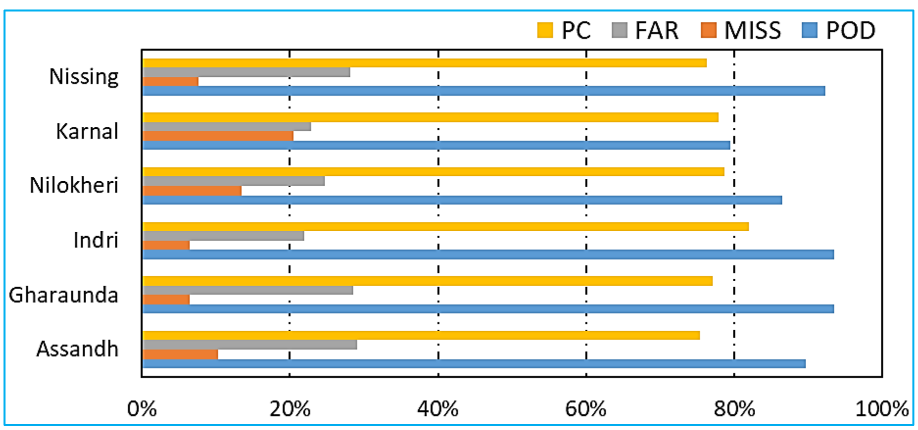


Fig. 3. Verification of Satellite Rainfall using INSAT 3DR H-E, 2021 with IMD

carried out and results are summarized in Fig. 2 & Table 2 for JJAS 2021. NK (0.41) block exhibited the highest Threat Score (TS) value for 2021. The highest Probability of Detection (POD) was observed for ID block (0.87). The highest Miss rate (M) is observed in GD block (0.29). The False alarm rate (FAR) is highest in both ID & KA blocks (0.48). The Heidke Skill Score (HSS) is highest for NK (0.32) block. NK (0.65) blocks exhibited the highest Percentage Correct (PC) score values.

5.3. *Validation of the performance of INSAT-3DR HE Product over the rain gauges of AS, GD, ID, KA, NK Blocks for 2021 (JJAS)*

The performance of INSAT-3DR Hydro-Estimator rainfall product is also evaluated over the rain gauges of AS, GD, ID, KA, NK Blocks for 2021 (JJAS) as shown in Fig. 3 & Table 3. The value of TS is highest in ID block (0.57) followed by NK block (0.55) and is lowest in NI

TABLE 4

Validation of Satellite Rainfall using INSAT 3DR H-E, 2021 with IMD Rain-gauges

Skill Score	AS	GD	ID	KA	NK
R	0.98	0.78	0.82	0.8	0.83
BIAS*	24.19	34.45	78.68	-87.12	32.27
RMSE*	54.16	80.4	101.83	177.88	77.36

(* the units of Bias, and RMSE are mm/month)

TABLE 5

Verification of Rainfall Forecast for Monsoon seasons of 2021 (JJAS) for 03 blocks of Karnal District by using INSAT-3DR HE Product (2 × 2 contingency table)

Year	Blocks	Total no. of days	Successful forecasting (days)	Forecast failure (days)	Accuracy (%)	No. of Hits (days)	No. of False Alarms (days)	No. of misses (days)	No. of correct prediction of no rain (days)
JJAS, 2021 w.r.t INSAT-3DR	MU	122	71	51	58.96	30	30	21	41
	KJ	122	73	49	59.83	35	35	14	38
	NI	122	71	51	58.19	40	30	21	31

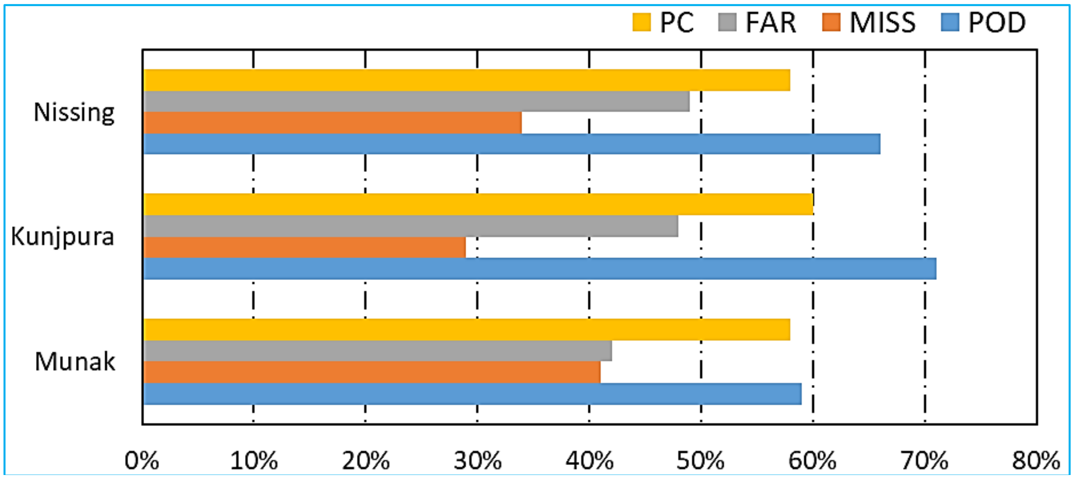


Fig. 4. Skill analysis of Rainfall Forecast for Monsoon seasons of 2021 (JJAS) for 03 blocks of Karnal District by using INSAT-3DR HE Product

TABLE 6

Skill analysis of Rainfall Forecast for Monsoon seasons of 2021 (JJAS) for 03 blocks of Karnal district by using INSAT-3DR HE Product

Skill Score	Using INSAT-3DR HE, JJAS 2021		
	Munak	Kunjpura	Nissing
TS	0.37	0.42	0.44
POD	0.59	0.71	0.66
MISS	0.41	0.29	0.34
FAR	0.42	0.48	0.49
HSS	0.16	0.22	0.16
PC	0.58	0.6	0.58

block (0.45). The POD is maximum for GD and ID blocks (0.94), followed by NI block (0.92) and is least for NK block (0.79). The M is highest for KA block (0.21) and lowest in ID and GD blocks (0.06). The F is the maximum for AS and GD blocks (0.29), followed by NI block (0.28) and is least in ID block (0.22). The value of HSS is maximum for ID block (0.60), followed by NK block (0.55) and it is least in AS block (0.47). INSAT-3DR, HE exhibited wet bias in all blocks with the exception of the KA block. In AS block INSAT-3DR, HE exhibited the highest correlation (0.98) with rain-gauges. The INSAT-3DR, HE, exhibited the highest RMSE of 177.88mm/month in the KA block (Table 4).

5.4. *Verification of Rainfall Forecast for MU, KJ, NI Blocks for 2021 (JJAS), by using INSAT-3DR Hydro-Estimator Product*

From the above discussion, the INSAT-3DR HE product correlates well with rain-gauges. Therefore, in the absence of actual rain-gauge data, the satellite-derived rainfall estimates can be used for the verification of rainfall forecasts. During the study period, the raingauge data was not available in MU, KJ, NI blocks of Karnal district. Therefore, the INSAT-3DR HE product is utilized for rainfall forecast verification. Table 4 depicts the 2×2 forecast verification contingency Table, for these three blocks for JJAS 2021, using INSAT-3DR HE product. The highest accuracy for successful forecasting is achieved for the KJ block (73 days *i.e.* 59.83%). The overall forecast accuracy range for JJAS 2021 is from 58.96% to 59.83%.

Based on the 2×2 contingency Table as shown in Table 5, the skill score analysis of the rainfall forecast is carried out and results are summarized in Fig. 4 & Table 6 for JJAS 2021. NI (0.44) block exhibited the highest Threat Score (TS) value for 2021. The highest Probability of Detection (POD) was observed for KJ block (0.71). The highest Miss rate (M) is observed in NI block (0.34). The False alarm rate (FAR) is highest in NI block (0.49). The Heidke Skill Score (HSS) and Percentage Correct (PC) score values are highest for KJ block (0.22) and (0.60).

6. Discussion

The analysis reveals varying levels of accuracy across the assessed regions. The Nilokheri block displayed the highest accuracy, with a successful forecast rate of 65.28%, while the Karnal block had the highest number of forecast failure days. The detailed evaluation of the INSAT-3DR Hydro-Estimator (HE) rainfall product's performance against rain-gauge data for the same regions and period. This evaluation highlights the potential for using satellite-derived rainfall estimates in regions where rain-gauge data is limited, underscoring the value of remote sensing observations in enhancing rainfall forecasts as also pointed out by Wang *et al*., 2023 during the verification of NWP models with satellite data in absence of rain-gauges.

These statistical findings hold significance as they reveal specific performance characteristics of the HE (Hydro-Estimator) rainfall product in different geographical blocks. The variation in the performance of INSAT-3DR HE product, underscores the diverse forecast performance across these geographical areas. A remarkable correlation of 0.98 with rain-gauges in the AS Block emphasizes the accuracy of this product in estimating rainfall in that area. Conversely, the KA Block's highest RMSE, standing at 177.88 mm/month, points to the need for improved forecasting or data quality or rainfall estimation algorithm changes for capturing heavy to extremely heavy rainfall from less convective systems in this region.

7. Conclusions

This study emphasizes the pressing need to improve rainfall forecast verification, specifically at the block level, where manned rain-gauges are non-uniformly distributed, posing significant operational and maintenance challenges. To fill this crucial observational gap, this research explores the use of remote sensing data from Meteorological Satellites, notably the Hydro-estimator (HE) rainfall product from INSAT-3DR. It showcases the efficacy of the INSAT-3DR HE product in both evaluating satellite-derived rainfall and verifying rainfall forecasts, marking a substantial leap in the field of rainfall forecast verification, underscoring the role of remote sensing technology in weather monitoring and prediction.

These observations shed light on the varying performance of rainfall estimation methods across distinct geographical zones, offering valuable insights for further enhancements and region-specific forecasting strategies. Analyzing and understanding such variations can provide valuable insights into the effectiveness of rainfall forecasts and may contribute to enhancing predictive models and preparedness strategies.

Disclaimer: The content and views expressed in this study are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

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