An overview of validation of meteorological products derived from INSAT-3D/3DR imager and sounder instruments

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ABSTRACT

Real-time meteorological products derived from INSAT-3D and INSAT-3DR satellites are very important in operational weather forecasting due to their larger spatial coverage and consistent availability. However, validation of the satellite-derived products is an essential step in ensuring accuracy and reliability of the products for integration in any specific application. The validation process involves comparing spatially and temporally co-located data obtained from satellites with ground-based observations as well as other sources of information to identify any discrepancy or error. In this paper, validation results of INSAT-3D/3DR satellite-derived meteorological products have been briefly discussed. Meteorological products derived from imagers and sounders onboard both satellites showed comparable error characteristics. As imager and sounder instruments of the upcoming INSAT-3DS satellite will have the same technical specification as INSAT-3D and INSAT-3DR satellites, these validation results will be helpful to improve the accuracy of geophysical products derived from INSAT-3DS satellite through fine-tuning of the existing algorithms.

Keywords: *Geostationary Satellite; Very High Resolution Radiometer; Infrared Sounder; Ground-based Observations; Error Characteristics.*

1. Introduction

Geostationary meteorological satellites are located at about 36000 km height from the Earth's surface and cover about one-third of the globe. The primary advantage of data and geophysical products derived from the geostationary meteorological satellites is their availability at finer spatial and temporal resolutions. India started its own geostationary meteorological satellite program namely, Indian National Satellite system (INSAT) in 1982, and currently two third-generation meteorological satellites viz., INSAT-3D and INSAT-3DR are in orbit. During the last 40 years of the INSAT program, several advancements in sensor characteristics and resolutions have been achieved (Kelkar, 2019; Bhatia and Mitra, 2021; Giri et al., 2023). Along with India, currently United States of America, Europe, Japan, China, Russia, and South Korea have their own geostationary meteorological satellites in orbit.

INSAT-3D and INSAT-3DR have four instruments viz., six-channel Very High Resolution Radiometer (VHRR) or imager, 19-channel atmospheric sounder, Data Relay Transponder (DRT), and Satellite-Aided Search & Rescue (SAS&R). The imagers onboard INSAT-3D and INSAT-3DR satellites are kept in staggered mode to obtain new set of data at 15-minute interval, even though the temporal resolution of each imager is 30-minute. INSAT-3DR imager has an additional capability of rapid-scan, which is usually activated during the development of tropical cyclones over the North Indian Ocean. During the rapid-scan, temporal resolution enhances to 4.5-minute for a selected sector of the full disk. The general specifications of INSAT-3D/3DR/3DS imager are given in Table 1. Atmospheric sounder onboard INSAT-3D satellite was decommissioned in 2020, and currently sounder onboard INSAT-3DR satellite is providing data at hourly temporal resolution. Table 2 provides general specifications of INSAT-3D/3DR/3DS sounder.

More than 50 geophysical products are operationally derived from the VHRR instrument and more than a dozen of distinct products are

Table 1. Specifications of INSAT-3D/3DR/3DS imager instruments.

Channel Number	Spectral Band	Spectral Interval (μm)	Spatial Resolution (km)
1.	Visible	0.55-0.75	1
2.	Shortwave Infrared (SWIR)	1.55-1.70	1
3.	Midwave Infrared (MIR)	3.80-4.00	4
4.	Water Vapour (WV)	6.50-7.10	8
5.	Thermal Infrared 1 (TIR1)	10.3-11.3	4
6.	Thermal Infrared 2 (TIR2)	11.5-12.5	4

Table 2. Specifications of INSAT-3D/3DR/3DS sounder instruments.

Channel Number	Detector	Central Frequency (μm)	Bandwidth (cm^{-1})	Principal Absorbing Gas	Purpose
1.	Longwave IR	14.67	13	CO_2	Stratosphere temperature
2.		14.32	13	CO_2	Tropopause temperature
3.		14.04	13	CO_2	Upper-level temperature
4.		13.64	16	CO_2	Mid-level temperature
5.		13.32	16	CO_2	Lower-level temperature
6.		12.62	30	Water Vapour	Total precipitable water
7.		11.99	50	Water Vapour	Surface temperature, moisture
8.	Midwave IR	11.04	50	Window	Surface temperature
9.		9.72	25	Ozone	Total ozone
10.		7.44	55	Water Vapour	Lower-level moisture
11.		7.03	80	Water Vapour	Mid-level moisture
12.		6.53	60	Water Vapour	Upper-layer moisture
13.	Shortwave IR	4.58	23	N_2O	Lower-level temperature
14.		4.53	23	N_2O	Mid-level temperature
15.		4.46	23	CO_2	Upper-level temperature
16.		4.13	40	CO_2	Boundary-layer temperature
17.		3.98	40	Window	Surface temperature
18.		3.76	100	Window	Surface temperature, moisture
19.	Visible	0.695	1000	Visible	Cloud

derived from the sounder instrument through a high-end Multi-mission Meteorological Data Receiving and Processing System (MMDRPS) at the India Meteorological Department (IMD), New Delhi (SAC, 2015; Giri et al., 2023). These meteorological products along with customized raw datasets have proven to be very useful in various applications such as operational weather forecasting, monitoring and nowcasting of convective weather events, tropical cyclone monitoring, numerical model data assimilation, agriculture, power, aviation, tourism, and renewable energy sectors.

In order to better utilize the meteorological products derived from imagers and sounders onboard INSAT-3D/3DR in any specific application and further advancement in retrieval algorithms, regular validation of these products are necessary. The validation of these products can be done either against in-situ observations or using other standard satellite products. Several independent studies have been carried out to validate some of the meteorological products derived from INSAT-3D/3DR satellites viz. imager-derived Outgoing Longwave Radiation (OLR; Yadav et al., 2022; Mishra et al., 2024), Upper Tropospheric Humidity (UTH; Dey et al., 2014), rainfall (Khan et al., 2021; Kumar et al., 2021, 2023; Malhan et al., 2022; Prakash and Bhan, 2023a, 2023b), Sea Surface Temperature (SST; Jangid et al., 2017), cloud microphysical properties (John et al., 2019), and Atmospheric Motion Vectors (AMVs; Sharma et al., 2021), and sounder-derived temperature and humidity profiles (Ratnam et al., 2016; Singh et al., 2017; Giri et al., 2022; Gopalkrishnan et al., 2023), and Total Precipitable Water vapour (TPW; Yadav et al., 2020, 2021).

IMD and Space Applications Centre (SAC) jointly validated most of the imager and sounder products of INSAT-3D/3DR for a rather shorter time period and a technical report was prepared (IMD, 2021). Although validation for a shorter time period would not provide robust error characteristics of any meteorological product, it would essentially provide a guidance regarding methodology and reference datasets to be used for further extensive validation studies. The objective of this paper is to summarize the validation results of meteorological products derived from INSAT-3D/3DR imager and sounder instruments. This consolidated review would be very useful for end users and algorithm developers. The INSAT-3DS satellite is supposed to be launched in early 2024, and the instrument characteristics of imager and sounder of INSAT-3DS is same as INSAT-3D/3DR. All meteorological products derived from INSAT-3D/3DR are going to be continued with INSAT-3DS satellite. Hence, this paper will be useful in fine-tuning the meteorological products derived from imager and sounder onboard INSAT-3DS satellite.

2. Validation of INSAT-3D/3DR imager-derived products

The imagers or VHRRs onboard INSAT-3D/3DR satellites operate in six wavelength bands namely, visible, shortwave infrared (SWIR), midwave infrared (MIR), water vapour (WV), thermal infrared-1 (TIR1), and thermal infrared-2 (TIR2). The spatial resolutions of visible and SWIR channels are 1 km, spatial resolutions of MIR, TIR1 and TIR2 are 4 km, and that of WV channel is 8 km (Table 1). The temporal resolutions of both imagers are 30-minute. However, both imagers are placed in staggered mode so that a new set of imager data and products could be obtained in 15-minute interval. About 50 geophysical products are derived in real-time from the VHRR data through the MMDRPS at IMD, New Delhi (Giri et al., 2023). These products along with raw data are shown to be very useful in various meteorological applications.

Table 3 shows error characteristics of INSAT-3D/3DR imager-derived major pixel-level products for rather shorter time period (IMD, 2021). As error characteristics of these satellite-derived products were computed for each month separately for INSAT-3D and INSAT-3DR satellites, the ranges of correlation coefficient, bias and root-mean-square error (RMSE) have been provided for all products hereafter. The preliminary inter-comparison of OLR products derived from INSAT-3D/3DR with the Clouds and the Earth’s Radiant Energy System (CERES) data showed very good agreement with each-other. The biases in

Table 3. Error characteristics of the INSAT-3D/3DR imager-derived major pixel-level products. RMSE and *r* stand for root-mean-square error and linear correlation coefficient, respectively.

Product Name	Reference Data	Validation Period	Error Characteristics
Outgoing Longwave Radiation (OLR)	CERES	Jan-Jun 2021	r = 0.97 to 0.99 Bias = -1 to 5 W/m^2 RMSE = 7 to 10 W/m^2
Upper Troposhperic Humidity (UTH)	Radiosonde	Nov 2020 to Jan 2021	r = 0.78 to 0.84 Bias = -2 to 1% RMSE = 11 to 14%
Sea Surface Temperature (SST)	In-situ (iQuam)	Mar-May 2021	Bias = -0.2 to 0.05 K RMSE = 0.6 to 0.8 K
Land Surface Temperature (LST)	MODIS (MYD11A1)	Jan-Jun 2021	r > 0.92 Bias = -3 to 1 K RMSE = 2 to 4 K
Cloud Mask (CMK)	Aqua-MODIS	Feb-Jul 2021	Accuracy = 0.86 to 0.87 Bias score = 0.66 to 0.68
	SNPP-VIIRS		Accuracy = 0.86 to 0.87 Bias score = 0.66 to 0.67
Cloud Top Pressure (CTP)	MODIS (MYD06)	May-Jun 2021	r = 0.90 to 0.94 Bias = 13 to 34 hPa RMSE = 109 to 121 hPa
Cloud Top Temperature (CTT)	MODIS (MYD06)	May-Jun 2021	r = 0.85 to 0.92 Bias = -3 to 3 K RMSE = 11 to 17 K
Cloud Particle Effective Radius (CER)	SNPP-VIIRS	Jun 2021 (Ocean only)	Bias = -2 to 6 micron RMSE = 7 to 10 micron
Cloud Optical Thickness (COT)	SNPP-VIIRS	Jun 2021 (Ocean only)	Bias = 5 to 7 RMSE = ~12

INSAT-3D/3DR derived OLR showed seasonal variations such as underestimation during the winter months and overestimation during the summer months. In addition, INSAT-3D derived OLR product has marginally smaller RMSE and larger correlation coefficient than INSAT-3DR derived OLR product (IMD, 2021). Daily gridded OLR product at 10 km × 10 km spatial resolution was also generated from the Global Space-based Inter-Calibration System (GSICS) corrected INSAT-3D imager data for 2014-2020 in order to generate daily climate data records, and bias of 5-6 W/m^2 was found against CERES data (Yadav et al., 2022). In addition, INSAT-3D derived OLR product showed better agreement with other satellite-derived OLR products such as Advanced Very High Resolution Radiometer (AVHRR) and High Resolution Infra-Red Sounder (HIRS) derived OLR products at daily and monthly scales (Mishra et al., 2024).

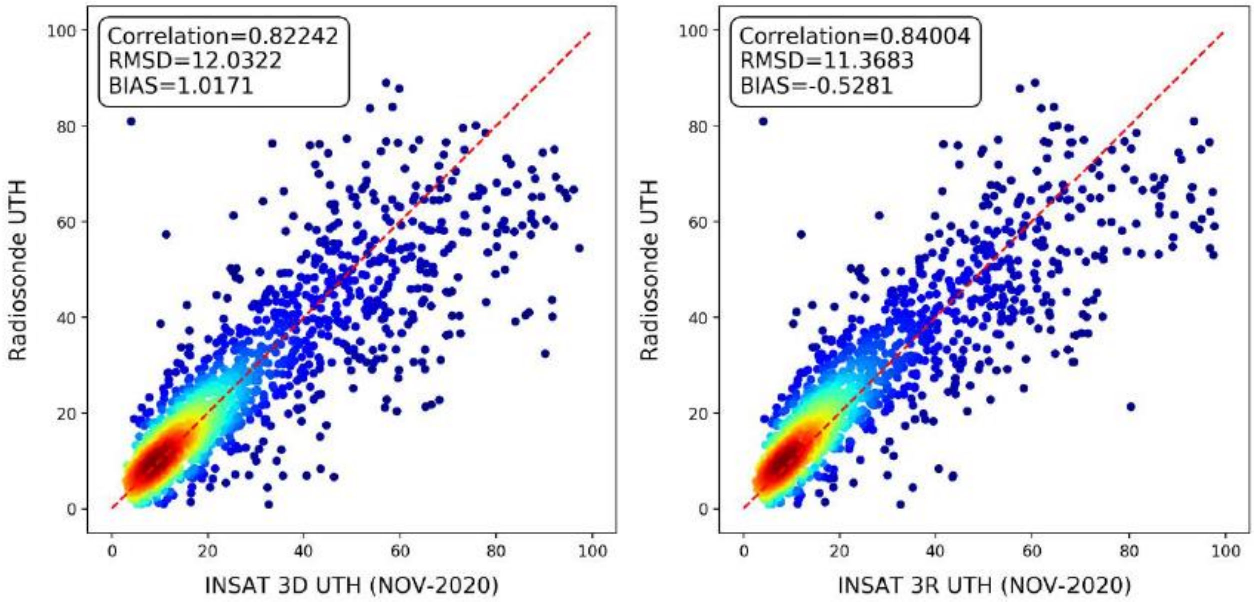

Figure 1: Comparison of upper tropospheric humidity products from INSAT-3D and INSAT-3DR imagers against radiosonde observations for November 2020.

For the validation of UTH product, quality-controlled IMD radiosonde profiles of relative humidity were used and UTH was calculated by taking the weighted average of relative humidity over WV weighting function. Figure 1 shows comparison of UTH from INSAT-3D and INSAT-3DR imagers against radiosonde observations for the month of November 2020. UTH derived from INSAT-3DR imager showed slightly better performance than INSAT-3D imager-derived UTH product (IMD, 2021). In an another study, UTH product derived from INSAT-3D imager was also validated against radiosonde observations for the first half of 2014 and correlation coefficients of 0.78-0.87 and RMSE of the order of 10% were reported (Dey et al., 2014). In addition, INSAT-3D derived UTH product showed comparable results with Meteosat-7 derived UTH product.

Clear-sky SST products derived from INSAT-3D/3DR imagers were initially validated against in-situ data from the in-situ SST Quality Monitor (iQuam) comprising observations from drifters, ships, and tropical and coastal moorings for the period of March-May 2021. SST derived from two algorithms viz., one-dimensional variational technique (1DVAR) and non-linear SST algorithm (NLSST) were considered, and better performance of 1DVAR than NLSST was observed for both imagers (IMD, 2021). This result is in good compliance with the earlier study by Gangwar and Thapliyal (2020). It was found that RMSE in SST products was exceptionally less than 1 K for both retrieval algorithms. Similar performance was also reported, when INSAT-3D derived SST was compared against buoy and Argo observations over the North Indian Ocean (Jangid et al., 2017).

Clear-sky LST products derived from INSAT-3D/3DR satellites were compared with the Moderate Resolution Imaging Spectroradiometer (MODIS) product for the first half of 2021. The comparison was done separately for different land cover types. Figure 2 shows comparison of LST products derived from INSAT-3D/3DR imagers with MODIS data for desert region. Both satellites provide comparable error characteristics which vary with land cover types (IMD, 2021).

The cloud mask products derived from INSAT-3D/3DR imagers were compared with MODIS and Suomi National Polar-orbiting Partnership - Visible Infrared Imaging Radiometer Suite (SNPP-VIIRS) products. During spatio-temporal co-location, threshold for maximum spatial distance between two datasets was limited to ± 2 km and the maximum temporal difference was limited to ± 6 minutes. Both satellite products showed similar characteristics. Cloud properties such as Cloud Top Pressure (CTP) and Cloud Top Temperature (CTT)

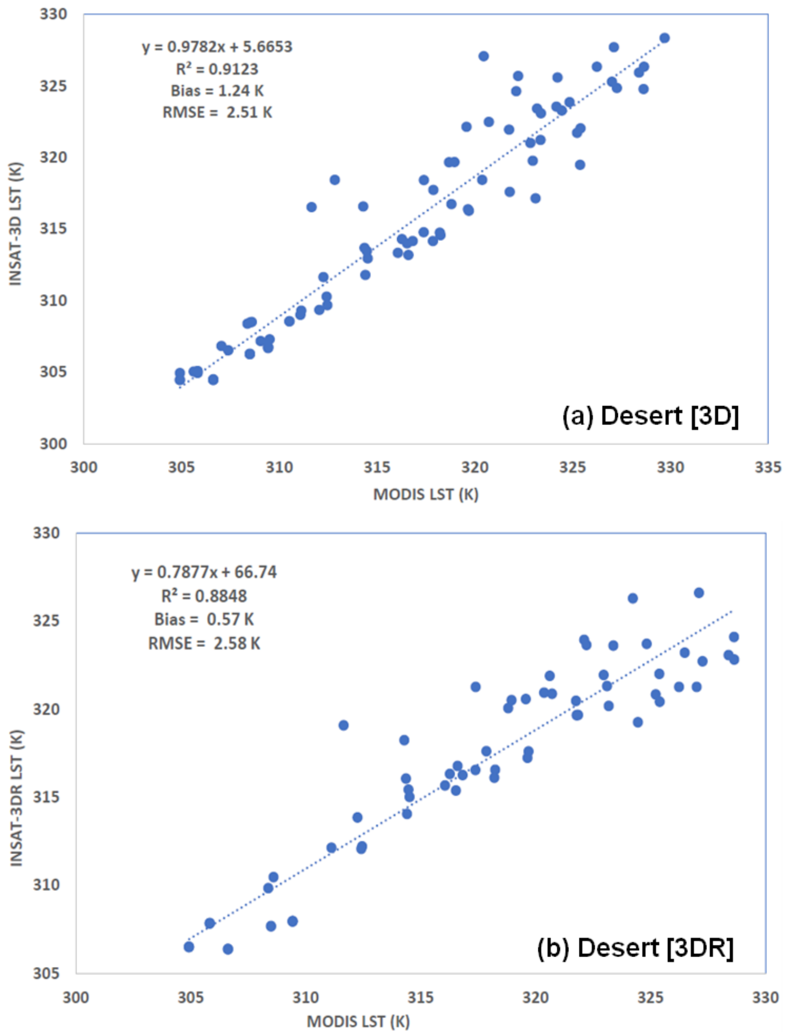

Figure 2: Comparison of land surface temperature products from (a) INSAT-3D and (b) INSAT-3DR imagers with MODIS data for desert region.

derived from INSAT-3D/3DR imagers were compared with MODIS products. Bias and RMSE in CTP product were found to be larger in INSAT-3DR product than INSAT-3D product. Figure 3 shows comparison of CTT products from INSAT-3D/3DR imagers with MODIS data for the months of May and June of 2021. Both INSAT-3D and INSAT-3DR products showed similar error characteristics. However, effective cloud emissivity products derived from INSAT-3D/3DR imagers could not be validated due to absence of corresponding validation dataset (IMD, 2021).

Two cloud microphysics products namely, Cloud particle Effective Radius (CER) and Cloud Optical Thickness (COT) derived from INSAT-3D/3DR imagers at pixel-level were compared with SNPP-VIIRS level 2 data over the Indian Ocean region for the month of June 2021. CER product derived from INSAT-3D had smaller bias and RMSE as compared to INSAT-3DR product. INSAT-3D derived COT product had larger bias than INSAT-3DR, but RMSE was comparable. Both CER and COT products derived from INSAT-3D were also compared with MODIS data, and higher correlation coefficients during cloudy months of July than less cloudy month of January were noticed (John et al., 2019).

Using half-hourly VHRR data of INSAT-3D/3DR satellites, four rainfall products viz., GOES Precipitation Index (GPI), INSAT Multispectral Rainfall Algorithm (IMR), Corrected IMR (IMC), and Hydro-Estimator Method (HEM) are operationally generated. These rainfall products are also made available at three-hourly and daily temporal accumulations. The spatial resolution of GPI product is 1° and that of IMR product is 0.1°,

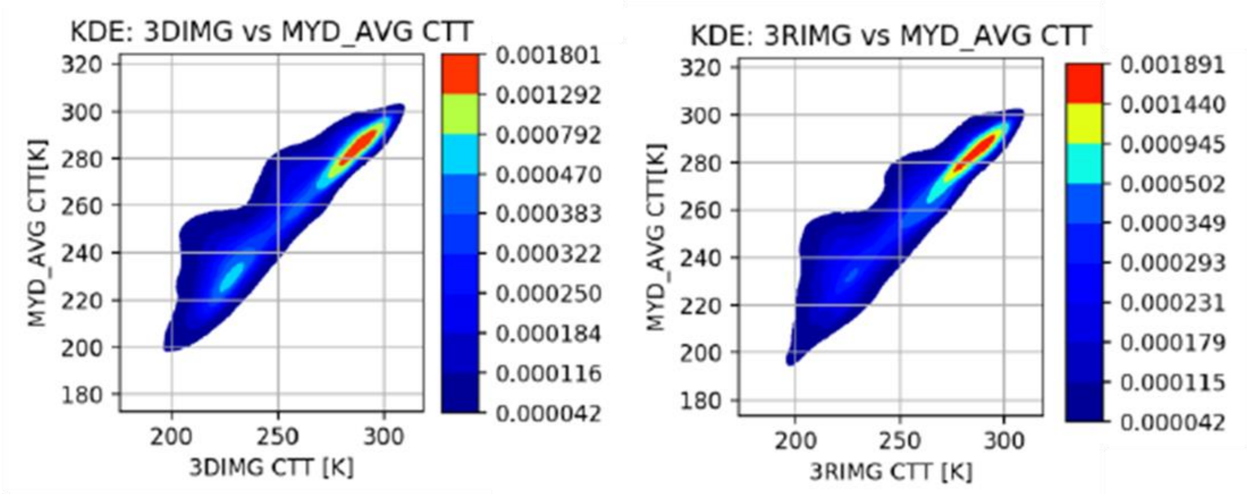

Figure 3: Comparison of cloud top temperature products from INSAT-3D and INSAT-3DR imagers with MODIS data for May-June 2021.

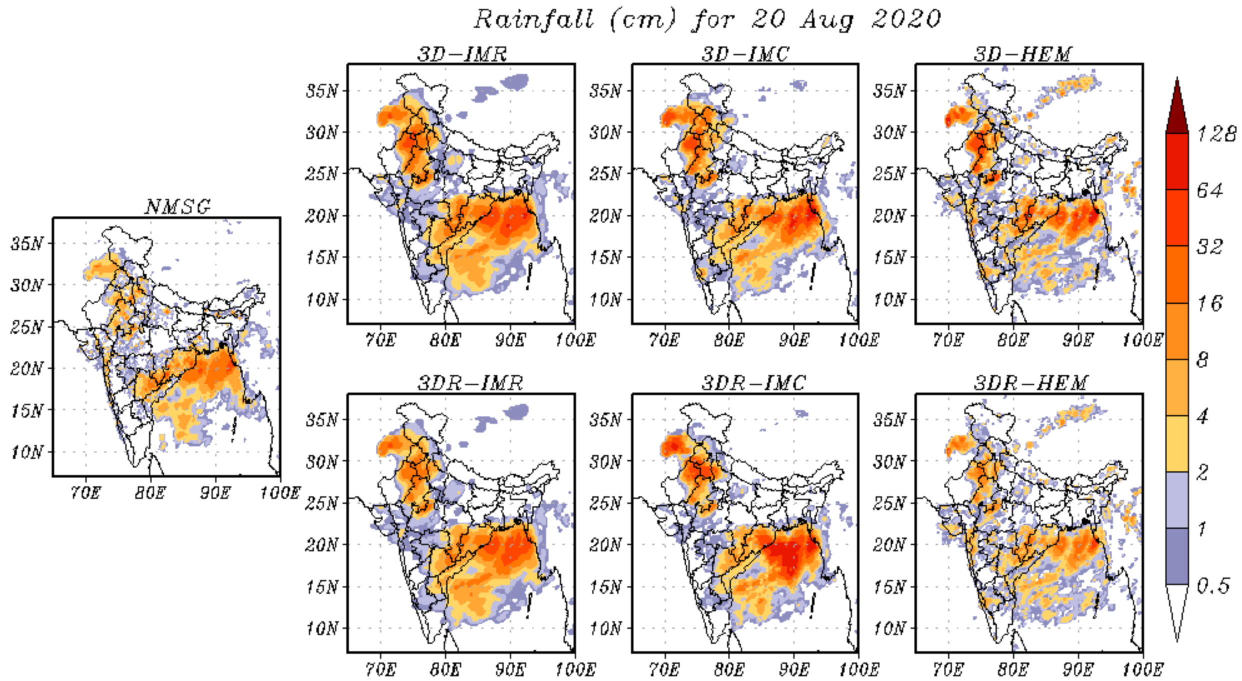

Figure 4: Spatial distributions of daily rainfall over the Indian region using a merged satellite-gauge data and INSAT-3D/3DR operational rainfall products for an active monsoon day.

whereas IMC and HEM products are pixel-level (~4 km) rainfall products. GPI product is suitable for large-scale rainfall estimation at longer temporal scale, whereas other three products are used for rainfall estimation at finer spatial and temporal scales. The spatial distributions of daily rainfall for an active monsoon day over the Indian region from IMR, IMC and HEM products are shown in Figure 4 from both INSAT-3D and INSAT-3DR satellites. Daily rainfall from a merged satellite-gauge rainfall product (Mitra et al., 2009; Prakash et al., 2018) is considered as reference for inter-comparison. INSAT-3D/3DR derived rainfall products show similar spatial distributions as reference data. But, there are quantitative differences in these products as compared to the reference data. Previous studies showed an improvement by IMC over IMR product in the southwest monsoon rainfall estimation (Khan et al., 2021; Prakash and Bhan, 2023b). But, no improvement in IMC over IMR was found during the tropical cyclone rainfall estimation (Prakash and Bhan, 2023a). In addition, IMR and IMC products were shown to be better for moderate monsoon rainfall estimation, while HEM was superior for

Table 4. Error characteristics of INSAT-3D/3DR imager-derived daily rainfall products. RMSE and *r* stand for root-mean-square error and linear correlation coefficient, respectively.

Product Name	Reference Data	Validation Period	Error Characteristics
Hydro-Estimator (HEM) Rainfall	Rain gauge	Jun-Sep 2020	*r* = 0.13 to 0.23 Bias = -14 to -8 mm/h RMSE = 21 to 27 mm/h
IMSRA Rainfall (IMR)	Rain gauge	Jun-Sep 2020	*r* = 0.12 to 0.26 Bias = -19 to -1 mm/h RMSE = 40 to 72 mm/h
Improved IMSRA (IMC) Rainfall	Rain gauge	Jun-Sep 2020	*r* = 0.21 to 0.29 Bias = -20 to 2 mm/h RMSE = 39 to 64 mm/h
GPI Rainfall	GPCP	Jun-Sep 2020	*r* = 0.58 to 0.74 Bias = -4 to -2 mm/day RMSE = 9 to 14 mm/day

Table 5. Error characteristics of INSAT-3D/3DR imager-derived atmospheric motion vectors (AMVs) and wind-derived products. RMSVD, Bias and STDV stand for root-mean-square vector difference, speed bias and standard deviation, respectively.

Product Name	Reference Data	Validation Period	Error Characteristics
TIR1 High Level (100-400 hPa)	Radiosonde	Jun 2021	RMSVD = ~5 m/s Bias = 0.1 to 0.2 m/s STDV = ~3 m/s
TIR1 Mid Level (400-700 hPa)	Radiosonde	Jun 2021	RMSVD = 4 to 5 m/s Bias = -0.8 to -0.6 m/s STDV = ~2 m/s
TIR1 Low Level (700-950 hPa)	Radiosonde	Jun 2021	RMSVD = 4 to 5 m/s Bias = -0.4 to -0.3 m/s STDV = ~2 m/s
WV High Level (100-400 hPa)	Radiosonde	Jun 2021	RMSVD = 5 to 6 m/s Bias = 0.8 to 0.9 m/s STDV = ~3 m/s
Visible Low Level (700-950 hPa)	Radiosonde	Jun 2021	RMSVD = 3 to 4 m/s Bias = -0.5 to -0.4 m/s STDV = ~2 m/s
MIR Low Level (700-950 hPa)	Radiosonde	Jun 2021	RMSVD = 3 to 4 m/s Bias = -0.2 to -0.05 m/s STDV = ~2 m/s
Wind-derived Products (atmospheric vorticity at 500, 700 and 850 hPa, upper-level divergence, lower-level convergence, deep-layer vertical wind shear, mid-level vertical wind shear, and 24-hr wind shear tendency)	Meteosat-8	During TCs Tauktae and Yaas	Qualitative only (large-scale features agreed well)

heavy to very heavy rainfall estimation over the Indian region (Kumar et al., 2021; Malhan et al., 2022). Table 4 shows error characteristics of INSAT-3D/3DR imager-derived rainfall products for the southwest monsoon season of 2020 during the joint IMD and SAC validation exercise.

The operational AMV products retrieved using four different spectral channels viz., visible, MIR, TIR1 and WV of imagers of INSAT-3D/3DR satellites at 4 km spatial resolution images are quantitatively assessed against radiosonde observations for the month of June 2021. The expected accuracy for lower level (>700 hPa) winds is 3-4 m/s, whereas it is 5-6 m/s for high-level (<400 hPa) winds (Deb et al., 2020). Table 5 shows error characteristics of AMVs derived from INSAT-3D/3DR imagers. Results indicate that AMVs derived from both

Table 6. Error characteristics of INSAT-3D/3DR imager-derived geophysical products primarily used for air quality monitoring and land surface & agro-meteorological applications. POD, POM, and POF stand for percentage of detection, percentage of miss, and percentage of false alarm, respectively.

Product Name	Reference Data	Validation Period	Error Characteristics
Aerosol Optical Depth (AOD)	Sky radiometer	Mar -May 2021	*r* = 0.49 to 0.91 Bias = -0.1 to 0.4 RMSE = 0.3 to 0.6
Fog Cover	Ground-based IMD observations	Jan 2021	POD = 0.40/0.54 (3D/R) POM = 0.60/0.46 (3D/R) POF = 0.13/0.28 (3D/R)
Fog Intensity			POD = 0.08 to 0.89 (3D) POD = 0.02 to 0.76 (3DR)
Smoke	SNPP-VIIRS & NASA FIRMS	Oct 2020	POD = 0.75/0.63 (3D/R) POF = 0.04/0.05 (3D/R)
Snow Cover	AWiFS	Jan-Feb 2019	Qualitative comparison only
Land Surface Albedo (LSA)	MODIS (MCD43C3)	Jan-Jun 2021	*r* = 0.45 to 0.92 Bias = -3 to -1% RMSE = 1 to 4%
Daily Insolation & Global Horizontal Irradiance (GHI)	Ground-based IMD observations	Jan-Dec 2020	*r* = 0.70 to 0.85 Bias = 3 to 12 MJm^{-2} RMSE = 3 to 5 MJm^{-2}
Net Radiation	Eddy covariance station data	Dec 2019 - Apr 2020	*r* = 0.66 to 0.81 RMSE = 31 to 56%
Actual Evapotranspiration (AET)	Eddy covariance station data	Jan-Dec 2020	*r* = 0.84 Bias = -24% RMSE = 0.42 mm/day
Potential Evapotranspiration (PET)	Eddy covariance station data	Jan-May 2020	*r* = 0.79 to 0.90 Bias = -15 to -1 % RMSE ~ 1 mm/day
Net Surface Shortwave Radiation over Ocean	RAMA buoy	Jan-Dec 2020	*r* = 0.75 to 0.92 RMSE = 20 to 50 Wm^{-2}

satellites have similar performances nearly within the expected accuracy. Better performances of INSAT-3D/3DR AMVs than Meteosat-8 AMVs were also reported in the earlier study (Sharma et al., 2021). However, accuracy of AMVs product depends on the accuracy of the registration of the images. These AMV products are regularly disseminated through the Global Telecommunication System (GTS) and assimilated in the global numerical models (Prasad et al., 2021; Sharma et al., 2021).

Moreover, qualitative assessment of wind-derived products such as convergence, divergence, vorticity, wind shear, etc. using AMVs of INSAT-3D was carried out using similar products available from the Co-operative Institute for Meteorological Satellite Studies (CIMSS) using Meteosat-8 satellite during two cyclones namely, Tauktae over the Arabian Sea and Yaas over the Bay of Bengal. The large-scale features were captured quite well by INSAT-3D/3DR AMV derived products during both tropical cyclones (IMD, 2021).

Several other geophysical products derived from INSAT-3D/3DR imagers such as aerosol optical depth, fog cover and intensity, smoke, snow cover, land surface albedo, and agro-meteorological products were also validated or compared collaboratively by IMD and SAC for a shorter time period (IMD, 2021). Table 6 summarizes error characteristics of these parameters.

3. Validation of INSAT-3D/3DR sounder-derived products

A nineteen channel (18 channels in IR and one channel in visible range) sounder paired with an imager instrument was first time mounted on

INSAT-3D satellite among INSAT-series satellites and later on INSAT-3DR satellite to provide atmospheric profiles of temperature and humidity. The sounder onboard INSAT-3D satellite decommissioned in September, 2020 and INSAT-3DR sounder is still providing useful data at hourly interval. Several meteorological products including vertical profiles of temperature, humidity and geopotential height along with Total Column Ozone (TCO), precipitable water vapour at three distinct atmospheric layers, TPW are operationally derived from INSAT-3D/3DR sounder for cloud-free regions. In addition, three thermodynamic indices namely, Lifting Index (LI), Dry Microburst Index (DMI) and Wind Index (WI) as well as products related to cloud properties such as CTP, CTT, effective cloud emissivity are also derived operationally from the sounder data (Giri et al., 2023). A comprehensive validation of these sounder-derived products is vital for their wider applicability in operational weather forecasting and for better understanding of the atmospheric dynamics.

An evaluation of INSAT-3D sounder-derived cloud-free profiles of temperature and humidity/water vapour with IMD radiosonde observations and other satellite data and reanalysis products over the Indian region showed that INSAT-3D products were able to show better coverage with high spatial and temporal resolutions (Ratnam et al., 2016; Singh et al., 2017). The sounder-derived products were shown to reproduce general features of temperature and humidity at daily and sub-daily scales reasonably well. Reasonably good correlation coefficient and bias of less than 0.5 K between sounder-derived temperature and radiosonde observations were noted except in the upper tropospheric and lower stratospheric regions where positive bias in the satellite product was between 2 K and 3 K. INSAT-3D sounder-derived humidity profiles showed comparable accuracies with the Atmospheric Infrared Sounder (AIRS) product onboard the Aqua satellite in the troposphere. However, temperature and humidity retrievals from INSAT-3D sounder over the land showed rather poor performance primarily in dry atmosphere (Singh et al., 2017). A comparison of INSAT-3D sounder-derived cloud-free TPW against ground-based Global Navigation Satellite System (GNSS) across India showed good correlation coefficients ranging 0.79-0.92 along with RMSE of 5.4-7.1 mm and bias of 2.1-4.7 mm (Yadav et al., 2020). Cloud-free TCO derived from INSAT-3D sounder was assessed against AIRS data and Dobson spectrophotometer observations over the Indian region for 2017 (Kumar et al., 2021). The comparison with AIRS product showed a correlation of 0.8, bias of -5 DU and RMSE of 15 DU with the best performance during the pre-monsoon season. INSAT-3D sounder-derived TCO had RMSE between 11 DU and 16 DU as compared to in-situ observations.

As instrument characteristics are same for the sounders onboard INSAT-3D and INSAT-3DR satellites, error characteristics of the sounder-derived products from both satellites are supposed to be comparable. INSAT-3DR sounder-derived cloud-free temperature profiles were compared with AIRS data and GPS-based radiosonde observations over the Indian sub-continent for September-December 2020 (Giri et al., 2022). The comparison with AIRS data showed an overall warm bias up to 2.5 K in INSAT-3DR product between 1000 hPa and 600 hPa. However, comparison of sounder-derived temperature profiles with radiosonde data showed rather larger range of bias between -3 K and 3 K with RMSE of the order of 4 K at all pressure levels (Giri et al., 2022). Better performance of temperature profile retrievals from INSAT-3DR sounder than INSAT-3D sounder is shown by Gopalkrishnan et al. (2023). An extensive evaluation of INSAT-3DR sounder-derived TPW product against GNSS observations over India for 2017-2018 showed linear correlation coefficients vary from 0.50 to 0.98 (Yadav et al., 2021). Although magnitude and sign of bias in INSAT-3DR product varied with station and season, RMSE values were larger during wet conditions than dry conditions. Furthermore, a preliminary validation of INSAT-3DR sounder products operationally generated through the MMDRPS at IMD was carried out jointly by IMD and SAC (IMD, 2021). The major results of this collaborative validation exercise are summarized in Table 7. Figure 5 shows an example of operational TPW product from INSAT-3DR sounder and comparison of this

Table 7. Error characteristics of INSAT-3DR sounder-derived products. RMSE, MSE and *r* stand for root-mean-square error, mean square error and linear correlation coefficient, respectively.

Product Name	Reference Data	Validation Period	Error Characteristics
Temperature Profiles	Radiosonde	Jan 2021	*r* = 0.6 to 0.95 Bias = -1.5 to 1 K RMSE = 1 to 2 K
	High resolution ECMWF analyses		Bias = -2 to 2 K RMSE = 0.5 to 3.5 K
Humidity/WV mixing ratio Profiles	ERA5 reanalysis	Jan 2021	*r* = 0.7 to 0.9 Bias = -40 to 5% RMSE = 10 to 50%
Geopotential Height Profiles	COSMIC-2	Jan 2021	Bias = -40 to 20 m RMSD < 1 m
Lifted Index (LI)	Radiosonde	Jan 2021	*r* = 0.82 Bias = 2.34 RMSE = 4.09
Total Column Ozone (TCO)	Dobson Spectrophotometer	Jan 2021	*r* = 0.57 Bias = -9 DU RMSE = 14 DU
	OMI/Aura		*r* = 0.83 Bias = 10 DU
	IASI/MetOp-B		*r* = 0.78 Bias = 7 DU
Total Precipitable Water Vapour (TPW)	SSMIS	Jan-Mar 2021	*r* = 0.96 to 0.99 Bias = 2 to 4 mm RMSE = 3 to 4 mm
Cloud Top Pressure (CTP)	MODIS (MYD06)	May-Jun 2021	*r* = 0.16 to 0.26 Bias = 28 to 87 hPa MSE = 240 to 278 hPa
Cloud Top Temperature (CTT)	MODIS (MYD06)	May-Jun 2021	*r* = 0.09 to 0.22 Bias = 10 to 20 K MSE = ~39 K

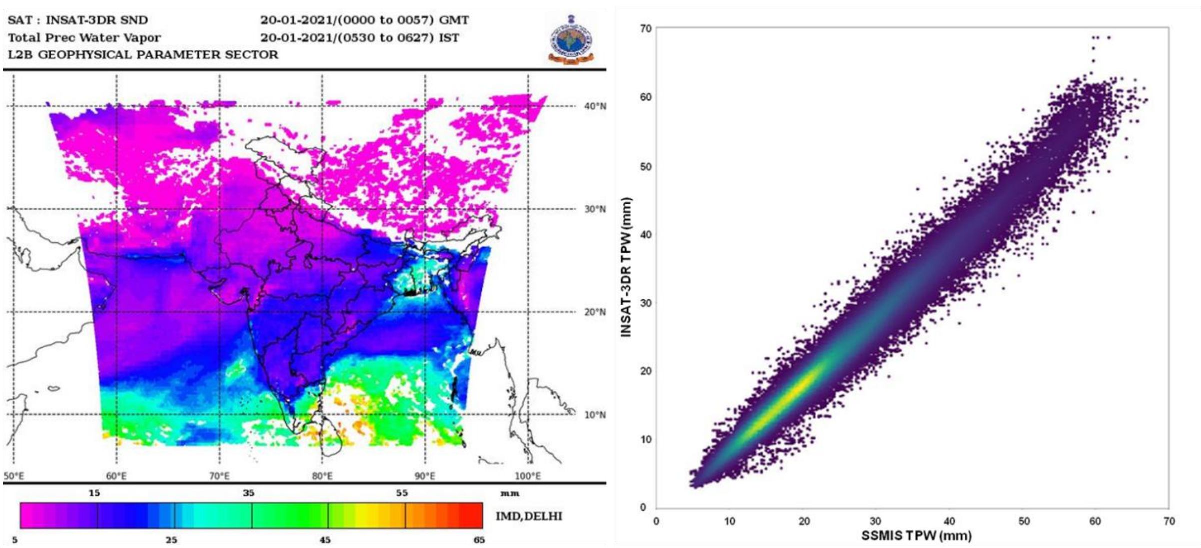

Figure 5: A sample TPW product derived from INSAT-3DR sounder over the Indian region (left panel) and comparison of cloud-free TPW from INSAT-3DR sounder and SSMIS product (right panel) for January 2021.

product with SSMIS satellite-based TPW product for January 2021. All meteorological products derived from INSAT-3DR sounder exhibited reasonably good correlation coefficients, smaller biases and RMSEs except for CTP and CTT products.

4. Conclusions

This paper provides an overview of validation results of meteorological products operationally derived from INSAT-3D/3DR imager and sounder instruments through the MMDRPS at IMD, New Delhi. These satellite-derived geophysical products are very useful in operational weather forecasting and to better understand the dynamics of several weather systems. As expected, satellite-derived meteorological products have unspecified bias and errors. An extensive and continuous validation exercise against ground-based observations and inter-comparison with other satellite data is vital for their wider applications and further improvement in retrieval algorithms. A collaborative preliminary validation exercise between IMD and SAC showed overall similar performances of meteorological products derived from INSAT-3D and INSAT-3DR satellites. The upcoming INSAT-3DS satellite will have the same instrument specification for both imager and sounder. Validation results from INSAT-3D/3DR products would essentially help to further improve the quality of meteorological products derived from INSAT-3DS satellite.

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