A Long-term Global Comparison of IMERG and CFSR with Surface Precipitation Stations

Uttam Ghimire
University of Guelph
Taimoor Akhtar
University of Guelph
Narayan Shrestha
University of Guelph
Pranesh Paul
University of Guelph
Christoph Schürz
Helmholtz Centre for Environmental Research UFZ Environmental Engineering and Biotechnology Research Unit: Helmholtz-Zentrum fur Umweltforschung UFZ Themenbereich Umwelt- und Biotechnologie
Raghavan Srinivasan
Texas A&M University Kingsville
Prasad Daggupati (pdaggupa@uoguelph.ca)
University of Guelph College of Physical and Engineering Science https://orcid.org/0000-0002-7044-3435

Research Article

Keywords: IMERG, CFSR, Global comparison, surface precipitation stations

Posted Date: June 29th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1650617/v1

Abstract

For data sparse conditions of developing countries, gridded meteorological products have potential for different hydro-climatic applications. Comparisons of IMERG precipitation, at 0.1^{o}, have been done with TRMM precipitation at station-, basin- and country-scale, in recent past. As IMERG products are expected to be available at least until mid-2030, a long-term global comparison of IMERG precipitation at station-scale, to guide their potential use, is highly desired. Therefore, we access surface precipitation stations from NOAA and compare their GSOM with IMERG at 0.1° during 2001–2020. Thus, we evaluate mean IMERG, CFSR and GSOM monthly precipitation with standard metrices like NSE, VE, KGE, R, RMSE and PBIAS for 5 geographical regions, 7 continents, 105 countries and > 50,000 surface locations. After comparison, we observe highest median NSE for Tropic of Capricorn (IMERG: CFSR = 0.85:0.59), followed by Antarctic (0.76:0.49), Arctic (0.71:0.32), Tropic of Cancer (0.64:0.14) and Frigid circle (0.47: -0.87). It shows satisfactory and unsatisfactory performances in the 'fourth/first' and 'last/remaining regions' for 'IMERG/CFSR', respectively. Fractional similarity of unit precipitation was good in Europe (VE = 0.72), North America (0.72), Asia (0.71), Australia (0.70) and satisfactory in South America (0.66) and Africa (0.52) for IMERG. Whereas, we find satisfactorily simulation for Europe (VE = 0.61), North America (0.56) and Australia (0.56), while other continents have unsatisfactory simulation of precipitation by CFSR. At country levels, 64 countries reveal a significantly better mean NSE with IMERG. While all these analyses pointed that IMERG monthly precipitation has better utility than CFSR in different hydro-meteorological applications, its site-specific application will still need detailed analysis at daily (sub-daily) resolutions. The outcomes of the study are expected to guide water resources managers to use these datasets in sustainable water resources management.

1. Introduction

Measurements of precipitation, a key hydrological variable, are sparsely and unevenly distributed over the globe (Kidd and Levizzani, 2011) and hardly represent the spatial rainfall patterns (Navarro et al., 2019). On the other hand, satellite precipitation products and their reanalysis products provide spatially inclusive precipitation estimates for large domains of the globe (Navarro et al., 2019). In addition, now a days, a large number of global gridded precipitation products exists. Differences in these data sets, however, exist due to their sources and their generation processes (Sun et al., 2017). However, gridded and continuous precipitation products can benefit studies in transboundary domains, and geographically challenging terrains, and data scarce regions. Thus, these data can provide leverage to researchers and water resources managers for different purposes like water resources assessment, master plans for basin, operational use in floods and drought monitoring and forecasting and to fill in the existing gaps of meteorological data (Polpanich et al., 2020). To be precise, popularity and applicability of these data products for hydro-meteorological applications are increasing, due to increasing accessibility, improvements in earth system representation in such models and high-speed computing allowing multiple petabytes of data to undergo different procedures in little to no time (Jiang and Wang, 2019).

An example of such satellite product is Tropical Rainfall Measurement Mission (TRMM) Multisatellite Precipitation Analysis (TMPA) (Huffman et al., 2010; Huffman et al., 2007) which is a near real-time product available from 2000 onwards. There are multiple applications of TMPA precipitation products in data scarce regions for hydro-climatic assessments (Hussain et al., 2018; Worqlul et al., 2017). Launched in February 2014, the Global Precipitation Measurement (GPM) mission consisted of a constellation of satellites to provide next generation of global observations of precipitation (Hou et al., 2014). As an advancement over TMPA, Integrated MultisatllitE Retrievals for GPM (IMERG) products were conceived which provided better spatial and temporal resolutions, snowfall estimates and unification of different satellite estimates (Huffman et al., 2015b; Huffman et al., 2020). Different versions of IMERG has been compared with other products and applied over the years (Table 1a).

In 2019, version 06 (V06) of IMERG was released, which estimates precipitation from different satellites under the GPM constellation at a high spatial (0.1°) and temporal (30') resolution (Huffman et al., 2020). Spatial coverage of this data extends from 90° N-S which was 60° N-S in previous versions of IMERG and temporal coverage has been extended from June 2000 onwards using TRMM (until 2014) and GPM (after 2014) estimates. Studies have suggested that IMERG V06 is an improvement over its predecessors (V05 and others) and other products in estimating sub-daily, daily and monthly rainfall in different studies (Table 1b).

In addition, early runs with minimum latency period are expected to help in real time flood forecasting applications but does not undergo different correction algorithm within the model. Late runs have latency period of almost 14 hours but undergoes forward and backward propagation of sensor and rainfall data within the algorithm of IMERG, allowing it to have a better accuracy than early runs. Similarly, Final runs are generated after almost 3 months of latency but have been recommended for research purposes by the data providers (GPM, 2020b). The Late and Final runs are similar in majority of the grid boxes and are generally different by an adjustment factor (Table 1c).

Table 1

a. Different versions of IMERG has been compared with other products and applied over the years

Author	Datasets to compare	Region/ Country	Application condition	Remarks
Gaona et al. (2016)	IMERG V03 with ground based radar rainfall maps	over land surface of Netherlands	At 30-minutes, daily, monthly and yearly time-steps	reported with a slight underestimation (2%), but also recommended as a reliable source of rainfall for locations devoid of rain gauge and radar coverage
Sahlu et al. (2016)	IMERG V03 with CMORPH	For Nile river basin	For a single wet season of 2014	reported for its outperformance with lesser bias and higher correlation with observed data
Asong et al. (2017).	IMERG V03 with surface measurements	Southern part of Canada	6-hourly and daily scales/ for a period of 2 years	where it showed similar regional variations of mean daily observed precipitation and its continuous and categorical verification revealed satisfactory agreement with observed precipitation at 6-hourly and daily scales
Lee et al. (2019)	IMERG V03 with CMORPH	East Asia		IMERG has been reported better than CMORPH in as well and has been recommended to be used as a reference precipitation data to validate numerical weather prediction models by
Zhang et al. (2019)	IMERG V03 and TMPA-3B42V7	Ganjing river basin China	Hydrological simulation	suggested that IMERG outperforms its competitors in daily flow simulation when fed to hydrological models
Dezfuli et al. (2017)	IMERG-V04, TMPA with surface rainfall stations	West and East Africa		that IMERG shows better agreement with gauge data in East Africa and humid West Africa compared to the southern Sahel, but had problems in capturing the annual cycle
Reddy et al. (2019)	IMERG V04 with GSMap-V6, INSAT3D, IMR, HEM and IMD-NCMRWF with gridded gauge-based IMD data	India	On daily, monthly and seasonal time steps	showed that all products had noticeable biases in precipitation in orographic regions and the difference in biases between the products were significant but with an overall better performance of IMERG-final and IMD-NCMRWF performed
Aslami et al. (2019)	IMERG V05 with surface rainfall station along with GsMap	A province of Iran		reported that IMERG rainfall was relatively closer to gauge records and thus recommended to be used as a replacement for gauge observation for data limited regions

Table 1
b. Application of IMERG V06

Author	Datasets to compare	Region/ Country	Application condition	Remarks
Tang et al. (2020)	IMERG- V06 with nine satellite and reanalysis datasets (i.e. PERSIANN-CDR, ERA5, TRMM, CMORPH, CHIRPS, SM2RAIN, ERA5, MERRA2, ERA-Interim and GSMap)	China	For hourly and daily rainfall simulation during 2000 to 2018 with a focus on snowfall estimates	reported its outperformance except GSMap. better performances were seen even at hourly and daily time-steps and in the representation of diurnal cycles. However, the snowfall simulation of IMERG was reported worse compared to other products.
Islam et al. (2020).	IMERG V06B Final run with five satellite products (TRMM, TMPA, CMORPH, PERSIANN and PERSIAN-CDR) and gauge based precipitation dataset	Australia	Over a 5-year period from 2014–2019 at 0.5° grid at daily, seasonal and annual scales	which revealed that IMERG and TMPA performed better than others

Table 1
c. Application of IMERG with different runs

Author	Datasets to compare	Region/ Country	Application condition	Remarks
Wang et al. (2017)	IMERG (final run), TMPA-3B42V7 with surface rainfall stations	Coastal region of China	Heavy rainfall simulation abilities during Typhoon of 2014–2015	IMERG shows overall better performance
Wu et al. (2018)	TMPA-3B42RT, IMERG (early run and late run) with 830 surface rainfall stations	Mainland China	At daily time-step during 2015–2016	both products overestimated light rainfall between 0.1–9.9 mm/day, underestimated moderate rainfall between 10-24.9 mm/day and extreme rainstorm above 250 mm/day
			Heavy rain between 25–50 mm	better performance
			light and moderate rainstorm (50-99.9 and 100-249.9 mm/day)	Performing better
				Early and late runs of IMERG generally improved performance both spatially and temporally, but were not distinct over dry seasons and dry areas
Liu (2016)	IMERG (final run) and TMPA 3B43	Both hemisphere of the earth	Monthly comparison	IMERG monthly product could capture major heavy precipitation regions in both hemispheres
Gadelha et al. (2019)	A grid level assessment of IMERG (final run)	4911 stations in Brazil		Reported that IMERG effectively captured the overall spatial rainfall patterns and could be a good source of rainfall data in ungauged areas over Brazil
Navarro et al. (2019)	Evaluation of IMERG (final run) with gridded observation (E-OBS) dataset	Europe	2014–2018	Showed a general overall agreement in spatial distribution of mean precipitation (R^2 = 0.8) but with discrepancies in mountainous Alps, coastlines and peninsulas. The pixels which had surface rain gauges were performing better than the pixels with no observation.

Author	Datasets to compare	Region/ Country	Application condition	Remarks
Sharifi et al. (2017)	A comparison of IMERG final and late run	62 ground stations in Austria	At sub-daily scales	Both products were reported to be overestimating the precipitation frequency than the observed
Tan and Santo (2018)	Compared IMERG early, late and final runs	501 surface stations in Malaysia	During 2014–2016	Revealed that the final run did not add improvement to the product and the early run itself has potential for use in real time flood monitoring. The application of IMERG in hydrological modeling has also added value to it.
Yuan et al. (2017)	The performance application of IMERG (final run) and TMPA-3B42V7	In a mountainous stream of Myanmar	Hydrological simulation	TMPA-3B42V7 was reported comparable and even better than IMERG when used for streamflow simulation. However, it has been reported that the results for only an year and thus the comparisons might not be robust.
Tapiador et al. (2020)	Validated IMERG v05B early, late and final runs	over Spain	Hydrological simulation	Reported its satisfactory performance in areas where no rain gauges were used for the calibration of IMERG and a very good performance in areas where at least one rain-gauge stations existed to calibrate the IMERG rainfall, thus yielding a very good performance in hydrological simulation.

While several studies have reported better performance of IMERG late and final runs than the early run to simulate observed rainfall characteristics (Sungmin et al., 2017), such differences may not be always distinct. For data scarce catchments, the differences between different runs of IMERG might not be significant.

Climate Forecast and System Reanalysis (CFSR) precipitation at 0.38° spatial resolution and daily temporal resolution has been one of the easily accessible precipitation products and thus widely used data for hydrological modeling, largely due to the easy to access web portal https://globalweather.tamu.edu/. The CFSR products have been officially referenced more than 5900 times in peer-reviewed literature, which shows its popularity and wide academic and research audience (Saha et al., 2010; Saha et al., 2014). However, there exists the gap that the data have been compared with IMERG in very less amount. The majority of comparison studies that analyze the IMERG products (in comparison to other precipitation products and observed rainfall) were performed mostly at surface rainfall stations, river basin and at most country level and for short time periods ranging from a few months to years (Table 1a, b, c). Thus, there is a need of global comparison of IMERG and CFSR with surface precipitation information over the entire period of IMERG (i.e. June 2000 onwards). Therefore, this study aims to compare the IMERG Final run, CFSR and surface precipitation information at multiple spatial scales (i.e. station, country, continent and geographical circles) during 2001–2020 which will serve as a guide for potential application of these data in data scarce regions of interest for sustainable water resources management. The results are expected to guide researchers whether IMERG has potential for application in different hydro-climatic studies, as IMERG is expected to be disseminating data till mid 2030s and beyond (GPM, 2020a).

2. Methodology

2. 1. Surface precipitation stations

From the National Oceanic and Atmospheric Administration web-portal https://www.ncei.noaa.gov/data/global-summary-of-the-month/archive/, the Global Summary of Month (GSOM), Version 1 was downloaded, consisting of monthly total precipitation from approximately 112,000 stations throughout the globe (Lawrimore et al., 2016). A subset of nearly 52,000 stations was finalized based on their availability of precipitation data during 2000–2020 with a minimum of 12 data points for comparison. The majority of the stations are located in the United States, Europe and Australia as can be seen from Fig. 1. A detailed list of the implemented stations is presented in Table S2.

It was also observed that the countries in Africa, Oceanic islands and south America were not adequately represented by the surface rainfall stations, indicating the common issue of data unavailability and lower data quality within developing countries.

2.2. IMERG precipitation

The current GPM constellation includes several microwave imagers and sounders from which precipitation is estimated using different algorithms (Huffman et al., 2015a). Different sensors from such imagers and sounders provide their own estimates of precipitation even after inter-calibration, mainly due to their time of observation, resolution, and sensor/algorithm limitations. Thus, different procedures are needed to create a uniformly gridded final product by combining information from all data sources. As such, IMERG is an integrated coding system incorporating unified algorithms to generate a single high-resolution product from the GPM constellation (Huffman et al., 2010; Huffman et al., 2018; Huffman et al., 2015a,b; Huffman et al., 2020; Huffman et al., 2019).

The precipitation estimates from different sensors of GPM constellation are computed using Goddard Profiling Algorithm (GPROF2017), gridded into 0.1 × 0.1° fields, intercalibrated to the GPM CORRA (Combined Radar Radiometer Algorithm) product which is the best snapshot of GPM estimate of rainfall, subjected to GPCP climatological adjustments, resulting into half-hourly time resolutions. This product then undergoes Climate Prediction Center Morphing-Kalman Filter (CMORPH-KF) (Joyce and Xie, 2011) time interpolation procedure and Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks- Cloud Classification System (PERSIAN-CCS) (Hong et al., 2004) infrared recalibration procedure. Parallelly, the MERRA2 and GEOS-FP vertically integrated vapor (TQV) fields are used in the CMORPH-KF procedure. The PERSIAN-CCS precipitation estimates are computed and sent to CMORPH-KF procedure which uses the passive microwave and infrared estimates of rainfall to create half-hourly estimates again. Thus, IMERG system gets run twice in near-real time.

For different latencies and accuracies, the IMERG runs are distinguished into three products: Early, Late and Final with their latency period of 4 hours, 14 hours, and 3 months, respectively. With increasing latency, different adjustment procedures are incorporated in the product due to which the accuracy also tends to increase. In the V06 of IMERG, the morphed precipitation covers 90^{o} N-S wherein latitude inside of 60^{o} N-S are expected to have higher accuracy due to the availability of both microwave and infrared products. In all the Early, Late and Final products, the "*precipitationcal*" variable persists which incorporates the correction factors and is expected to be more accurate than "*precipitationuncal*". During the entire data series from June 2000 onwards, TRMM provided the CORRA till 2014 and GPM provided the CORRA afterwards. For the bias profile to incorporate correction, GPCP satellite-gauge product provides the climatology. The developer team has recommended Early run of IMERG for immediate purposes like flash flood forecasting and monitoring, Late run for crop forecasting and Final run for research purposes. Early run can also be understood as the quick estimate of the precipitation while final run is the one which uses monthly GPCC gauge data to create finer and more accurate product. Also, the developers have revised the maximum precipitation rate within the IMERG from 50 to 200 mm/hr to account the interest of researchers in the rainfall extremes (Huffman et al., 2015b; Huffman et al., 2020).

For this study, we chose IMERG V06 Final run and downloaded its monthly product from the NASA web portal (https://gpm1.gesdisc.eosdis.nasa.gov/data/GPM_L3/GPM_3IMERGM.06/). The global data was downloaded and extracted for above discussed 52,000 locations using customized scripts in R. The only variable in the final run was the "*precipitation*", unit of which was in mm and the time was from June 2000 to till date, which was extracted for this study.

2.3. CFSR precipitation

The Climate Forecast System Reanalysis (CFSR) is a reanalysis gridded meteorological product which was designed to provide the best estimate of the state of the coupled atmosphere, ocean, and land surface sea ice system. It assimilates the satellite radiances over the coupled atmosphere ocean system with an interactive sea-ice model and provides different variables like precipitation, maximum temperature, minimum temperature, and other meteorological information. CFSR precipitation data during 2000–2020 were accessible as two different formats and versions through the National Center for Atmospheric Research (NCAR) as version 1 (Saha et al., 2010) and version 2 (Saha et al., 2014), the latter one having data from 2011 onwards. We selected NCEP CFSR (https://rda.ucar.edu/datasets/ds093.2/) and NCEP CFSR Version 2 (CFSv2) (https://rda.ucar.edu/datasets/ds094.2/) monthly products and downloaded the variable "*total precipitation*" for this study. The gridded precipitation product was regular monthly means (4 per day) of 6-hour accumulated (initial + 0 to initial + 6) precipitation and the accessible resolutions were 0.5^{o} and 2.5^{o}, of which we chose the former one.

2.4. Comparison metrics

The details of comparison metrics are presented in Supplementary section S1.

2.5. Spatial scales of analysis and presentation

The comparison results are presented spatially at each geographical region, continent, country, and station levels. Administrative boundaries for the world, continent and country are referred from Thematic Mapping website (Sandvik, 2009). Mean precipitation and their spreads are compared at geographical regions while spatial-plots of different metrices are presented at country and station levels. Geographical regions are differentiated as Tropic of Cancer (0^{o}-23.5^{o}N), Tropic of Capricorn (0^{o}-23.5^{o}S), Arctic Circle (23.5^{o}N-66.5^{o}N), Antarctic Circle (23.5^{o}S- 66.5^{o}S) and Frigid zone (Warman, 1959) in this study. Similarly, Africa, Asia, Australia, Europe, North America, Russia, and South America are the continents identified in this study. While the authors are aware that Russia is not a continent, its sheer size (country with largest land area in the world) warranties a separate analysis. Also, Antarctica has been omitted from this analysis due to its dominance of snow over rainfall and absence of any reported stations in GSOM. The median of comparison metrices are calculated from stations located inside country administrative boundary to provide country estimate. A total of 105 countries are identified based on the spatial information used. A representative station density is also calculated for each country using number of stations used in this study and the land area of country, accessed from Worldometer (2020), to provide confidence in our assessments at country levels.

3. Results And Discussion

3.1. Geographical regions

A quick inspection of geographical regions revealed that the Tropic of Cancer had a total of 2868 stations, for which an average of 72–133 (31–58% of total) points of monthly precipitation values were available for evaluation, with majority of them lying within India, Thailand, Mexico, and China. Within Tropic of Capricorn, 1421 stations were available with 63–196 (27–81%) points with high coverage in Australia and very limited representation of other countries. The Arctic circle had highest number of stations (41639) with an average of 37–164 (16–71%) points, mostly from USA and Europe with relatively sparse distribution across central Asia. The Antarctic circle had 6592 stations (majority in Australia) with an average of 97–219 (42–96%) points and the Frigid circle had the least (349) number of stations with 73–211 (32–92%) points used to evaluate precipitation products in this study.

A comparison of normal (long-term average) mean monthly precipitation of stations within each geographical region during 2001–2020, simulated by IMERG, CFSR and GSOM is presented in Fig. 2.

From Fig. 2, it is evident that there is comparable to better simulation of normal mean monthly GSOM precipitation by IMERG, compared to the CFSR product for all geographical regions. A relatively better capture of normal monthly precipitation by both products is seen for Frigid circle, Arctic circle and Tropic of Capricorn compared to the Antarctic circle and Tropic of Cancer. Similarly, CFSR has higher spread of precipitation compared to IMERG in the Tropic of Cancer, Arctic, and the Frigid circle and IMERG has higher spread in remaining two. The other performance metrices calculated at stations and aggregated for geographical regions also exhibit a clear signal regarding IMERG's outperformance in simulating mean monthly precipitation across the globe.

The NSE values computed during the period of 2001–2020 with monthly precipitation values of IMERG, CFSR and GSOM indicate that IMERG has better ability to simulate wet months than CFSR for each region, as shown in Fig. 3.

The bias of NSE towards the higher values indicates that bigger NSE values indicate better capture of wet season's climatology in the region, which might be important from flood simulation and monitoring perspective. The highest value of median NSE was observed for Tropic of Capricorn (0.85), followed by Antarctic (0.76), Arctic (0.71), Tropic of Cancer (0.64) and Frigid circle (0.47) for IMERG which indicates its good performance in the former three regions, satisfactory performance in the fourth and unsatisfactory in the fifth region. CFSR on the other hand had a satisfactory performance in the Tropic of Capricorn (NSE = 0.59), followed by unsatisfactory performance in Antarctic (0.49), Arctic (0.32), Tropic of Cancer (0.14) and Frigid circle (-0.36). While these median values are representative of the region, individual stations will have better (or worse) performance than this.

Not only during the high precipitation months, dry months in general also had better simulation of GSOM precipitation characteristics with IMERG for all geographical circles, as presented as VE values in Fig. 4. VE in general represents how much of the rainfall is delivered at the proper time and its remainder represents the fractional volumetric mismatch and is thus desired by water resources managers (Ghimire et al., 2019).

In terms of fractional volume match of unit precipitation, Arctic circle had the best statistics (median VE = 0.72) followed by Antarctic (0.7), Tropic of Capricorn (0.68), Frigid circle (0.62) and Tropic of Cancer (0.57) when simulated by IMERG. These statistics indicate good deliverance of unit monthly precipitation in the first two and satisfactory performance in the latter three regions. CFSR on the other hand had satisfactory simulation of unit precipitation in Arctic (VE = 0.57) and Antarctic circle (0.57) and unsatisfactory performance in remaining three regions. This indicates that researchers aiming to employ IMERG dataset in the Tropic of Cancer and Frigid circle can expect higher fractional mismatch compared to observed precipitation. Similarly, water resources management in the data scarce regions of Tropics and Frigid might not be benefitted by the monthly rainfall series of CFSR dataset. The relatively poor performance of both datasets in frigid circle could be due to their inability of estimating snow properly, as discussed by Huffman et al. (2020). Similarly, the relatively lower efficiency of the datasets in tropical circles could be due their inability to depict primary climatological features of tropical rainfall like annual mean, annual cycle and monsoon domain, as discussed by Wang and Ding (2008).

As above discussed metrices; NSE and VE measure relative agreement among observed and simulated precipitation values, RMSE however measures the differences between GSOM and IMERG (CFSR). Although an ideal value of RMSE would be zero, it is almost unachievable in rainfall comparison studies like this, but a larger value would indicate higher problems with the data associated. However, a geographical comparison of the precipitation products again revealed that IMERG has lesser errors than CFSR in simulating monthly precipitation across all geographical regions, as presented in Fig. 5.

In general, it is observed that RMSE of both products was highest in the Tropic of cancer, followed by Tropic of Capricorn, Arctic, Antarctic, and Frigid circles. While the stations number are different in each circle, this descending order of RMSE values are suggested to be evaluated qualitatively. The Indian subcontinent, southeast Asia and Amazon (i.e., the two tropical circles) generally receive higher precipitation than other regions of globe, thus any inconsistency there is likely to appear in higher quantities than the other geographical regions (Cobon et al., 2020). However, less disagreement (indicating less errors) is observed for IMERG when compared to the surface precipitation. In general, CFSR underperformed in estimating surface precipitation characteristics in all geographical circles at monthly time step.

The biases (percent) in IMERG and CFSR products are found in general to be positive, indicating overestimation of monthly precipitation by both products, as shown in Fig. 6.

IMERG (CFSR) had least median biases in Tropic of Capricorn i.e. 5.9% (0.4%), followed by Antarctic i.e. 8.6% (0.8%), Arctic i.e. 9% (11.5%), Tropic of Cancer i.e. 12.9% (24.7%) and Frigid circle i.e. 28% (60.35%). The spread of biases is smaller in IMERG compared to the CFSR, which indicates its slight overestimation in all geographical regions. However, the bias itself might not a significant issue in using such meteorological information from satellite products, mostly due to different bias correction techniques known to reduce systematic biases in estimated rainfall series compared to the observed rainfall climatology (Ghimire et al., 2019). A similar outperformance of IMERG over CFSR compared to GSOM precipitation is observed for two other metrices KGE and R, as shown in Figures S1 and S2, respectively.

The difference in the mean of performance metrices for each geographical region tested for their significance using Welch T-test reveals that IMERG is significantly better in simulating precipitation compared to CFSR, as presented in Table 2.

Table 2
Mean of performance metrices computed for IMERG and CFSR precipitation and their P values when tested for the significance for each geographical region

Region	Arctic circle	Antarctic circle	Tropic of Cancer	Tropic of Capricorn	Frigid circle
NSE_IMERG	0.56	0.68	0.39	0.73	-0.04
NSE_CFSR	-0.11	0.43	-0.66	0.42	-0.88
P_NSE	0.00	0.00	0.00	0.00	0.00
KGE_IMERG	0.68	0.74	0.54	0.74	0.47
KGE_CFSR	0.45	0.64	0.12	0.62	0.17
P_KGE	0.00	0.00	0.00	0.00	0.00
VE_IMERG	0.66	0.67	0.48	0.62	0.51
VE_CFSR	0.47	0.55	0.18	0.46	0.19
P_VE	0.00	0.00	0.00	0.00	0.00
R_IMERG	0.86	0.89	0.83	0.92	0.82
R_CFSR	0.71	0.77	0.75	0.81	0.74
P_R	0.00	0.00	0.00	0.00	0.00
RMSE_IMERG	30.35	24.02	72.68	49.99	22.35
RMSE_CFSR	45.76	32.57	114.48	73.92	31.58
P_RMSE	0.00	0.00	0.00	0.00	0.00
PBIAS_IMERG	13.19	10.21	15.86	10.06	34.36
PBIAS_CFSR	23.01	1.53	37.17	2.19	70.86
P_PBIAS	0.00	0.00	0.00	0.00	0.00

The outperformance of IMERG over CFSR could be due to different correction algorithms used by IMERG (Huffman et al., 2015b). Furthermore, IMERG uses GPCP monthly climatology to correct its biases (Huffman et al., 2018), albeit at a coarser resolution of 2.5°(Pendergrass et al., 2020). Better statistic values are observed in general for Arctic and Antarctic circles followed by tropic of Capricorn, tropic of Cancer and frigid circle, which is likely due to the better representation of precipitation in the GPCP and also the set of satellites which are continuously recording the energy information. The reason of low capture of precipitation values in the tropics of cancer and Capricorn could also be due to the missing of key monsoon characteristics of the region (Wang and Ding, 2008).

3.2. Continent wise comparison

A comparison of different precipitation stations located inside each continent revealed that IMERG outperforms CFSR in all continents in terms of different performance metrices. Figure 7 presents VE values computed for each continent by comparing IMERG (CFSR) with GSOM precipitation during 2001–2020.

The fractional matching of unit precipitation was good in Europe (VE = 0.72), North America (0.72), Asia (0.71), Australia (0.70) and satisfactory in South America (0.66), Russia (0.58) and Africa (0.52) when IMERG was used to simulate monthly precipitation during 2001–2020. However, when CFSR was used to simulate monthly precipitation, only Europe (VE = 0.61), North America (0.56) and Australia (0.56) were found satisfactorily simulated, while other continents had unsatisfactory simulation of precipitation for water resource management. Africa, which was least represented in this study due to the unavailability of rainfall stations reported for 2001–2020 had least utility of both IMERG and CFSR product evaluated in this study. A similar trend of other performance indicators (NSE, KGE and R) for the continents are presented in Figures S3, S4 and S5, respectively.

The disagreement of IMERG (CFSR) with GSOM precipitation represented by RMSE is presented in Fig. 8.

In general, South America had the largest median RMSE values (48.21 mm) followed by Asia (31.67 mm), North America (28.47 mm), Russia (24.21 mm), Africa (21.83 mm), Australia (21.78 mm) and Europe (21.75 mm) when IMERG was used to simulate monthly precipitation during 2001–2020. CFSR also followed a similar spatial trend, albeit with larger errors in South America (74.84 mm), Asia (53.66 mm), North America (44.89 mm), Russia (31.26 mm), Australia (31.58 mm), Europe (28.65 mm) and Africa (26.55 mm). The monsoon dominating Southeast Asia makes it the region where highest rainfall occurs throughout the globe (Mason et al., 2020). Similarly, northern part of South America, the Amazon receives good amount of rainfall (Liebmann and Allured, 2005), which increases the chances of getting larger RMSE values in this study. Similarly, both datasets are found to overestimate the overall monthly precipitation across all continents. Highest biases indicating overestimating nature are observed for IMERG (CFSR) in Russia: 36.8% (48.8%), Africa: 25.5% (1.4%), Europe: 21.5% (28.4%), South America: 16% (3.2%), Asia: 12.7% (12.2%), Australia: 7.9% (0.4%) and North America: 7.8% (9.6%) respectively, as presented in Figure S6. These median biases for both IMERG and CFSR in Russia indicate that unless systematic biases are removed from these products, they are unsatisfactory for hydro-meteorological applications. Application of relevant bias correction techniques can improve the IMERG (CFSR) precipitation's ability in other continents as well.

A larger confidence can be put on the results of IMERG compared to CFSR, as reflected by the results of comparing multiple performance indicators for their significance using Welch T-test in Table S3.

3.3. Country wise comparison

The metrices (NSE, VE, KGE, RMSE, R and PBIAS) computed at stations selected in this study were aggregated by their median value and presented at country level. These results are expected to guide researchers seeking to potentially use IMERG/CFSR data at their country of interest. While these statistics presented in this study are an indication for their potential application, it must be understood that they might not reflect the ground reality, as many countries have very few to no stations included in this analysis. Figure S7 presents the density of rainfall stations (number of stations per 1000 sq.km of land area) in different countries selected in this study. From Figure S7, it is evident that the countries located in South America, Africa and Asia have scarce representation of GSOM rainfall stations compared to the countries in Australia, Europe, and North America. As such, higher confidence can be placed on the results where station densities are higher than the ones with minimum to no representative coverage (Tian et al., 2018). Accordingly, the median of NSE values computed for stations located inside each country by comparing IMERG (CFSR) and GSOM precipitation during 2001–2020 are presented as spatial-plots in Fig. 9.

A significant difference among IMERG and CFSR generated NSE is observed at country levels when compared with GSOM precipitation. 64 out of 105 countries where more than one stations were available for comparison revealed that the mean NSE difference between IMERG and CFSR were significant with $P < 0.05$. A far superior performance of IMERG is evident at country levels throughout the globe with majority of countries in North America, Europe, Asia, and Australia having satisfactory to good performance. However, countries like Mongolia, Kazakistan, middle east Asian nations, Indonesia, Papua New Guinea, and many countries from Africa and South America exhibit unsatisfactory simulation of high rainfall months, attributed as poor NSE values. CFSR, on the other hand have only few countries with satisfactory simulation of wet months. Again, this superior performance of IMERG may be attributed to the set of passive and active satellite estimates of rainfall and further correction techniques employed with GPCP precipitation (Huffman et al., 2020; Huffman et al., 2019). When tested for significance of these differences between IMERG and CFSR, similar outperformances of IMERG at country level are observed in other indices like VE, KGE and R, which are presented in Figures S8, S9 and S10, respectively. The disagreement among the precipitation products, represented by RMSE values, aggregated at country level are shown in Fig. 10.

Despite low agreement among IMERG and GSOM precipitation across certain countries like Mongolia, Egypt, Iraq and others, as indicated by NSE values (Fig. 9), VE (Figure S8), KGE (Figure S9) and R (Figure S10), the RMSE values appear on the lower spectrum (Fig. 10). It is due to the arid climatology of these countries, where even low RMSE values could cause significant disagreement among rain/no rain status. Interestingly, CFSR appears to follow the trend of IMERG for majority of the countries, albeit with higher disagreement (higher RMSE values). The biases between IMERG (CFSR) and GSOM precipitation are accordingly calculated and presented in Figure S11. Similarly, the summary of statistics is presented in Table S4 for 138 countries which aligns with the above-discussed findings of better performance of IMERG compared to the CFSR.

3.4. Station wise comparison

Comparison of monthly precipitation at station levels during 2001–2020 for selected 50,000 + stations across the globe provides a clear snapshot that IMERG Final run has higher accuracy than CFSR in simulating precipitation. For e.g. the VE values computed at station levels clearly show an outperformance of IMERG precipitation, as can be seen from Fig. 11.

Similar outperformance of IMERG data over CFSR can be seen in terms of other metrices like NSE (Figure S12), KGE (Figure S13) and R (Figure S14). The disagreement among data in terms of RMSE also shows the higher RMSE values in stations located in South and Southeast Asia and Amazon forests with a clear outperformance of IMERG, as shown in Fig. 12.

The biases computed at station levels are presented in Figure S15 and the entire statistics can be referred at station levels from Table S5.

4. Conclusion

This study is the first to compare, to the knowledge of authors, IMERG with another readily available CFSR dataset in simulating the rainfall, using a set of performance indicators like NSE, VE, KGE, R, RMSE and PBIAS, for 5 geographical regions, 7 continents, 105 countries and 50,000 plus surface stations. Moreover, this study has been conducted to provide a more robust understanding of performance of IMERG at global scale using readily available data for more than 50,000 surface stations and for a period of almost two decades (2001–2020). The results clearly indicate that

- IMERG has a satisfactory to good simulation of monthly rainfall in majority of the regions, continents, countries, and stations and outperforms CFSR.
- IMERG had good simulation of observed precipitation in Tropic of Capricorn (median NSE = 0.85), Antarctic (0.76), Arctic (0.71) and satisfactory simulation in Tropic of Cancer (0.64) and unsatisfactory simulation in Frigid (0.47) region.
- Similarly, CFSR had satisfactory simulation of observed precipitation in Tropic of Capricorn (median NSE = 0.59) and unsatisfactory simulations in Antarctic (0.49), Arctic (0.32), Tropic of Cancer (0.14) and Frigid regions (-0.36).
- The fractional matching of unit precipitation was good in Europe (VE = 0.72), North America (0.72), Asia (0.71), Australia (0.70) and satisfactory in South America (0.66), Russia (0.58) and Africa (0.52) when IMERG was used to simulate monthly precipitation during 2001–2020.
- However, when CFSR was used to simulate monthly precipitation, only Europe (VE = 0.61), North America (0.56) and Australia (0.56) were found satisfactorily simulated, while other continents had unsatisfactory simulation of precipitation for water resource management.
- Along with the significant outperformance of IMERG over CFSR precipitation in geographical regions and continents, 64 out of 105 countries where more than one stations were available for comparison also revealed that the mean NSE difference between IMERG and CFSR were significant with $P < 0.05$, with a better performance from IMERG.

- In general, the stations also revealed a better simulation of monthly GSOM precipitation with IMERG rainfall product.
- The outcomes of the study are expected to guide water resources managers to use these datasets in sustainable water resources management.
- However, owing to the sparse to nil station density in many of the countries, the confidence in the results for many countries still need to be verified and thus the authors caution the potential users to dive into an in-depth analysis of different data products before finalizing them for research and application.
- Similarly, the IMERG V06 and Final run, which has been recommended by the developer team for research has been used for evaluation of precipitation simulation abilities and may differ from other versions and runs.
- Furthermore, application of IMERG or CFSR in hydrological model demands their daily or sub-daily formats of data, which was not evaluated in this study because such data was not available for a larger domain.
- Other verification measures like binary verification regarding rain/no rain status, categorical verification like different ranges of precipitation and their distribution verification are recommended before utilizing the IMERG or CFSR data for project and research use at daily (or sub-daily use).

Declaration

Acknowledgements, Statements & Declarations

-Ethical Approval: The authors acknowledge the approval of Dr. Andrey Savtchenko, Dr. George Huffman, and Andrea M. Portier from NASA Global Precipitation Measurement Mission to use and redistribute the IMERG data for use and analysis in this study. Similarly, the approval of Dr. Wei Shi from Climate Prediction Center, NOAA to use the CFSR data and redistribute is also acknowledged.

-Consent to Participate: We agree among us to outline the roles and responsibilities towards one another throughout the whole research and publication process.

-Consent to Publish: We all consent to publish

-Authors Contributions: Uttam Ghimire: Conceptualization, data management, analysis, First draft; Taimoor Akhtar: analysis and review of draft; Narayan Kumar Shrestha: analysis and review of draft; Pranesh Kumar Paul: review of draft; Christoph Schürz: review of draft, Raghavan Srinivasan: review of draft, Prasad Daggupati: project management and review of draft.

-Funding: This research was funded by the Natural Science and Engineering Research Council of Canada Discovery Grant (#401257).

-Competing Interests: There is no competing interest between us.

-Availability of data and materials: Due to privacy, ethical concerns and confidentiality agreements the supporting data can not be made available. However, we have provided the source and name of the contact persons in 'Acknowledgements, Statements & Declarations' section. We can provide more details on 'how to request data' to the peers upon request. Supplementary files: WRM (ctrl+click to follow the link).

References

1. Aslami,F., Ghorbani,A., Sobhani,B., Esmali,A., 2019. Comprehensive comparison of daily IMERG and GSMaP satellite precipitation products in Ardabil Province, Iran. International Journal of Remote Sensing 40, 3139-3153
2. Asong,Z., Razavi,S., Wheater,H., Wong,J., 2017. Evaluation of integrated multisatellite retrievals for GPM (IMERG) over southern Canada against ground precipitation observations: A preliminary assessment. Journal of hydrometeorology 18, 1033-1050
3. Cobon,D.H., Baethgen,W.E., Landman,W., Williams,A., van Garderen,E.A., Johnston,P., Malherbe,J., Maluleke,P., Kgakatsi,I.B. , Davis,P., 2020. Agroclimatology in grasslands. Agroclimatology: Linking Agriculture to Climate 60, 369-423
4. Dezfuli,A.K., Ichoku,C.M., Huffman,G.J., Mohr, K.I., Selker,J.S., Van De Giesen,N., Hochreutener,R., Annor,F.O., 2017. Validation of IMERG precipitation in Africa. Journal of Hydrometeorology 18, 2817-2825
5. Gadelha,A.N., Coelho,V.H.R., Xavier,A.C., Barbosa,L.R., Melo,D.C., Xuan,Y., Huffman,G.J., Petersen,W.A., Almeida,C.d.N., 2019. Grid box-level evaluation of IMERG over Brazil at various space and time scales. Atmospheric Research 218, 231-244
6. Gaona,M.R., Overeem,A., Leijnse,H., Uijlenhoet,R., 2016. First-year evaluation of GPM rainfall over the Netherlands: IMERG day 1 final run (V03D). Journal of Hydrometeorology 17, 2799-2814
7. Ghimire,U., Srinivasan,G., Agarwal,A., 2019. Assessment of rainfall bias correction techniques for improved hydrological simulation. International Journal of Climatology 39, 2386-2399
8. GPM, 2020a. Global Precipitation Measurement : Two decades of precipitation measurement
9. GPM, 2020b. What are the differences between IMERG Early, Late, and Final Runs, and which should be used for research?
10. Hong,Y., Hsu,K.-L., Sorooshian,S., Gao, X., 2004. Precipitation estimation from remotely sensed imagery using an artificial neural network cloud classification system. Journal of Applied Meteorology 43, 1834-1853
11. Hou,A.Y., Kakar,R.K., Neeck,S., Azarbarzin,A.A., Kummerow,C.D., Kojima,M., Oki,R., Nakamura,K., Iguchi,T., 2014. The global precipitation measurement mission. Bulletin of the American Meteorological Society 95, 701-722
12. Huffman,G.J., Adler,R.F., Bolvin,D.T., Nelkin,E.J., 2010. The TRMM multi-satellite precipitation analysis (TMPA), Satellite rainfall applications for surface hydrology. Springer, pp. 3-22

13. Huffman,G.J., Bolvin,D.T., Braithwaite,D., Hsu,K., Joyce,R., Kidd,C., Nelkin,E.J., Sorooshian,S., Tan,J., Xie,P., 2018. A Quick Summary of IMERG Versions and Features
14. Huffman,G.J., Bolvin,D.T., Nelkin,E.J., 2015a. Day 1 IMERG final run release notes. NASA/GSFC: Greenbelt, MD, USA
15. Huffman,G.J., Bolvin,D.T., Nelkin,E.J., 2015b. Integrated Multi-satellitE Retrievals for GPM (IMERG) technical documentation. NASA/GSFC Code 612, 47
16. Huffman,G.J., Bolvin,D.T., Nelkin,E.J., Tan,J., 2020. Integrated Multi-satellitE Retrievals for GPM (IMERG) Technical Documentation
17. Huffman,G.J., Bolvin,D.T., Nelkin,E.J., Tan,J., Braithwaite,D., Hsu,K., Joyce,R., Kidd,C., Sorooshian,S., Xie,P., 2019. Early Results for Version 06 IMERG
18. Huffman,G.J., Bolvin,D.T., Nelkin,E.J., Wolff,D.B., Adler,R.F., Gu,G., Hong,Y., Bowman, K.P., Stocker,E.F., 2007. The TRMM multisatellite precipitation analysis (TMPA): Quasi-global, multiyear, combined-sensor precipitation estimates at fine scales. Journal of hydrometeorology 8, 38-55
19. Hussain,Y., Satgé, F., Hussain, M.B., Martinez-Carvajal, H., Bonnet, M.-P., Cárdenas-Soto, M., Roig, H.L., Akhter,G., 2018. Performance of CMORPH, TMPA, and PERSIANN rainfall datasets over plain, mountainous, and glacial regions of Pakistan. Theoretical and applied climatology 131, 1119-1132
20. Islam,M.A., Yu,B., Cartwright,N., 2020. Assessment and comparison of five satellite precipitation products in Australia. Journal of Hydrology, 125474
21. Jiang,D., Wang,K., 2019. The role of satellite-based remote sensing in improving simulated streamflow: A review. Water 11, 1615
22. Joyce,R.J., Xie,P., 2011. Kalman filter–based CMORPH. Journal of Hydrometeorology 12, 1547-1563
23. Kidd,C. and Levizzani, V., 2011. Status of satellite precipitation retrievals, Hydrol. Earth Syst. Sci., 15, 1109–1116, https://doi.org/10.5194/hess-15-1109-2011
24. Lawrimore,J., Ray,R., Applequist,S., Korzeniewski,B., Menne,M., 2016. Global Summary of the Month (GSOM), version 1. NOAA National Centers for Environmental Information 10, V5QV3JJ5
25. Lee,J., Lee,E.-H., Seol,K.-H., 2019. Validation of Integrated MultisatellitE Retrievals for GPM (IMERG) by using gauge-based analysis products of daily precipitation over East Asia. Theoretical and Applied Climatology 137, 2497-2512
26. Liebmann,B., Allured,D., 2005. Daily precipitation grids for South America. Bulletin of the American Meteorological Society 86, 1567-1570
27. Liu, Z., 2016. Comparison of integrated multisatellite retrievals for GPM (IMERG) and TRMM multisatellite precipitation analysis (TMPA) monthly precipitation products: initial results. Journal of Hydrometeorology 17, 777-790
28. Mason,B.J., Loewe,F.P., Smith,P.J., 2020. World distribution of precipitation. Encyclopædia Britannica
29. Navarro,A., García-Ortega,E., Merino,A., Sánchez,J.L., Kummerow,C., Tapiador,F.J., 2019. Assessment of IMERG precipitation estimates over Europe. Remote Sensing 11, 2470

30. Pendergrass,A., Wang,J.-J., (Eds)., N.C.f.A.R.S., 2020. The Climate Data Guide: GPCP (Monthly): Global Precipitation Climatology Project
31. Polpanich,O.-U. , Ghimire,U. , Bhatpuria,D. , Piman,T., 2020. An Updated Assessment of Water Resource Modelling Capacity and its results used in policy process in Asia and the Pacific. Stockholm Environment Institute (SEI).
32. Reddy,M.V., Mitra,A.K., Momin,I.M., Mitra,A.K., Pai, D., 2019. Evaluation and inter-comparison of high-resolution multi-satellite rainfall products over India for the southwest monsoon period. International Journal of Remote Sensing 40, 4577-4603
33. Saha,S., Moorthi,S., Pan,H.-L., Wu,X., Wang,J., Nadiga,S., Tripp,P., Kistler,R., Woollen,J., Behringer,D., 2010. The NCEP climate forecast system reanalysis. Bulletin of the American Meteorological Society 91, 1015-1058
34. Saha,S., Moorthi,S., Wu, X., Wang,J., Nadiga,S., Tripp,P., Behringer,D., Hou,Y.-T., Chuang,H.-y., Iredell, M., 2014. The NCEP climate forecast system version 2. Journal of climate 27, 2185-2208
35. Sahlu,D., Nikolopoulos,E.I., Moges,S.A., Anagnostou,E.N., Hailu,D., 2016. First evaluation of the Day-1 IMERG over the upper Blue Nile basin. Journal of Hydrometeorology 17, 2875-2882
36. Sandvik,B., 2009. Thematic Mapping API: World Borders Dataset
37. Sharifi, E., Steinacker,R., Saghafian,B., 2017. Hourly comparison of GPM-IMERG-final-run and IMERG-real-time (V-03) over a dense surface network in Northeastern Austria. EGUGA, 1949
38. Sun,Q., Miao,C., Duan,Q., Ashouri,H., Sorooshian,S., & Hsu,K. L. (2018). A review of global precipitation data sets: Data sources, estimation, and intercomparisons. *Reviews of Geophysics*, *56*(1), 79-107
39. Sungmin,O., Foelsche,U., Kirchengast,G., Fuchsberger,J., Tan,J., Petersen,W.A., 2017. Evaluation of GPM IMERG Early, Late, and Final rainfall estimates using WegenerNet gauge data in southeastern Austria. Hydrology & Earth System Sciences 21
40. Tan,M.L., Santo,H., 2018. Comparison of GPM IMERG, TMPA 3B42 and PERSIANN-CDR satellite precipitation products over Malaysia. Atmospheric Research 202, 63-76
41. Tang,G., Clark,M.P., Papalexiou,S.M., Ma,Z., Hong,Y., 2020. Have satellite precipitation products improved over last two decades? A comprehensive comparison of GPM IMERG with nine satellite and reanalysis datasets. Remote Sensing of Environment 240, 111697
42. Tapiador,F.J., Navarro,A., García-Ortega,E., Merino,A., Sánchez, J.L., Marcos,C., Kummerow,C., 2020. The Contribution of Rain Gauges in the Calibration of the IMERG Product: Results from the First Validation over Spain. Journal of Hydrometeorology 21, 161-182
43. Tian,F., Hou,S., Yang,L., Hu,H., Hou,A., 2018. How does the evaluation of the GPM IMERG rainfall product depend on gauge density and rainfall intensity? Journal of Hydrometeorology 19, 339-349
44. Wang,B., Ding,Q., 2008. Global monsoon: Dominant mode of annual variation in the tropics. Dynamics of Atmospheres and Oceans 44, 165-183

45. Wang,R., Chen,J., Wang,X., 2017. Comparison of IMERG level-3 and TMPA 3B42V7 in estimating typhoon-related heavy rain. Water 9, 276
46. Warman,H.J., 1959. Map Meanings: A Teacher—Student Guide for Map Learnings in the Secondary Schools. Journal of Geography 58, 217-225
47. Worldometer, 2020. Largest Countries in the World (by area)
48. Worqlul,A.W., Yen,H., Collick,A.S., Tilahun,S.A., Langan,S., Steenhuis,T.S., 2017. Evaluation of CFSR, TMPA 3B42 and ground-based rainfall data as input for hydrological models, in data-scarce regions: The upper Blue Nile Basin, Ethiopia. Catena 152, 242-251
49. Wu,L., Xu,Y., Wang,S., 2018. Comparison of TMPA-3B42RT legacy product and the equivalent IMERG products over mainland China. Remote Sensing 10, 1778
50. Yuan,F., Zhang,L., Win,K.W.W., Ren,L., Zhao,C., Zhu,Y., Jiang,S., Liu,Y., 2017. Assessment of GPM and TRMM multi-satellite precipitation products in streamflow simulations in a data-sparse mountainous watershed in Myanmar. Remote Sensing 9, 302.
51. Zhang,Z., Tian,J., Huang,Y., Chen,X., Chen,S., Duan,Z., 2019. Hydrologic evaluation of TRMM and GPM IMERG satellite-based precipitation in a humid basin of China. Remote Sensing 11, 431

Figures

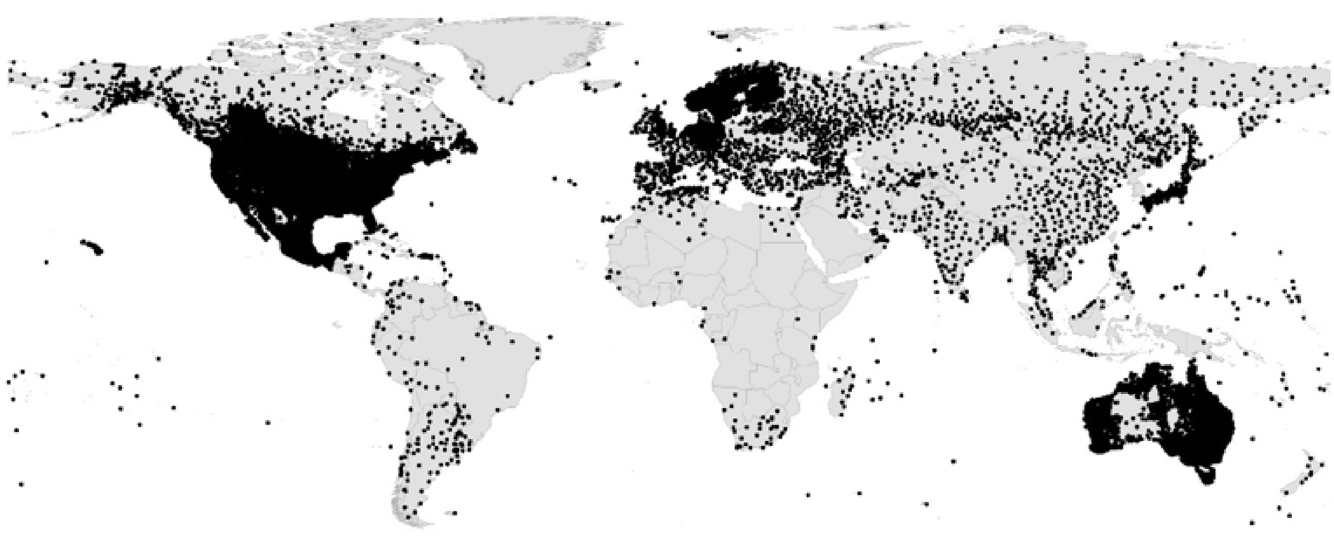

Figure 1

Surface precipitation stations selected for comparison during 2001-2020

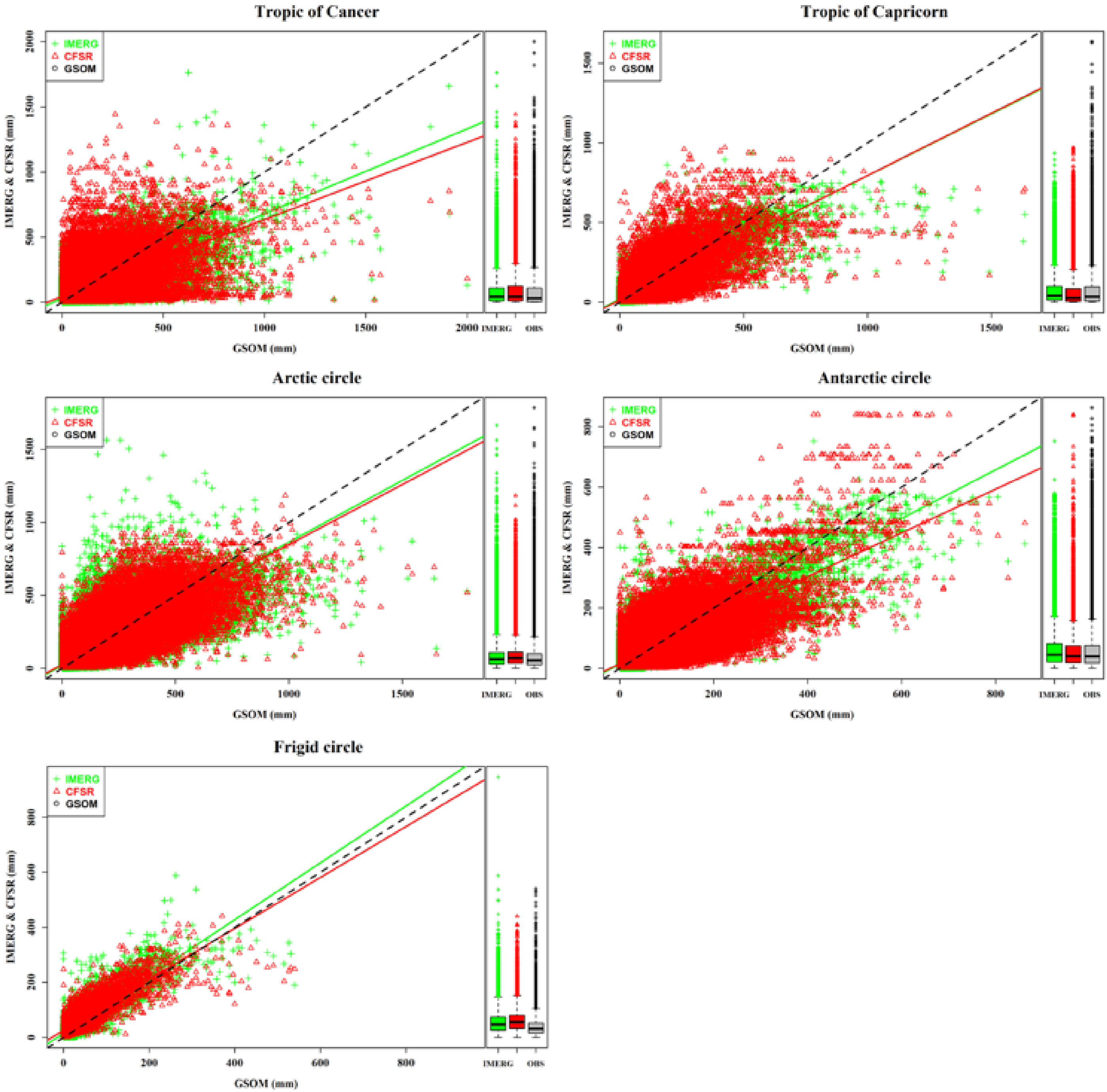

Figure 2

Scatter-plots & box-plots of mean monthly normal precipitation (mm) simulated by IMERG (green-cross) and CFSR (red-triangle) compared with observed GSOM (black circle) at stations during 2001-2020 across different geographical regions

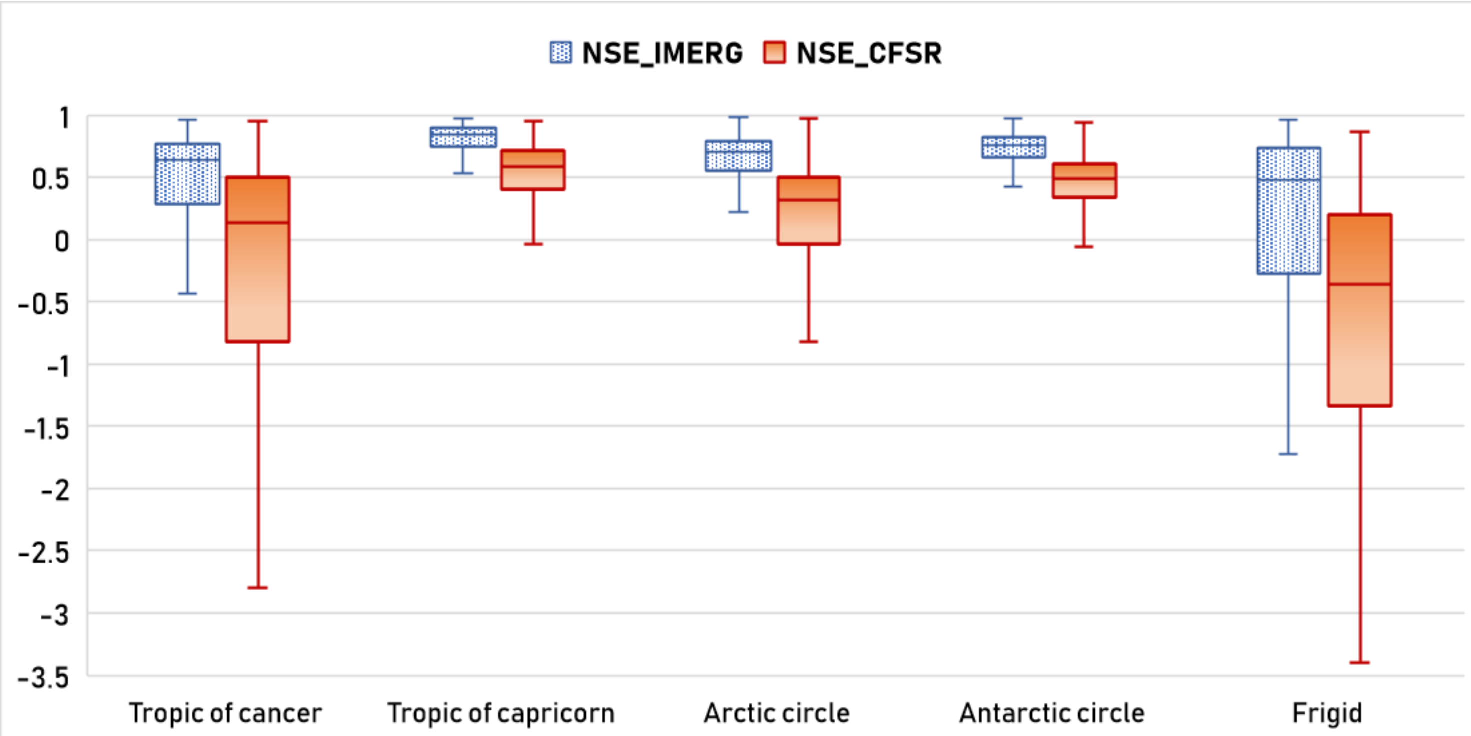

Figure 3

NSE values computed using monthly values of IMERG, CFSR and GSOM precipitation during 2001-2020 for different geographical regions

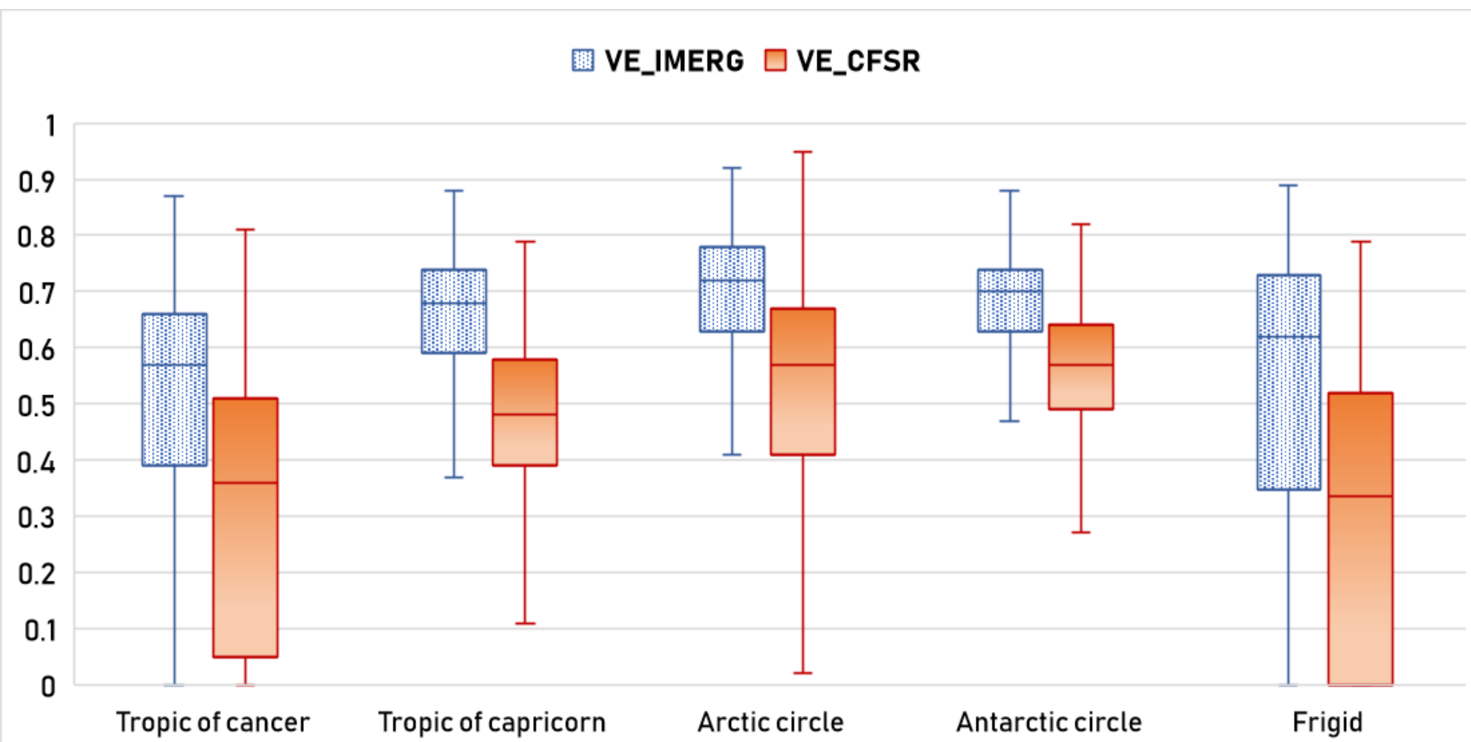

Figure 4

VE computed using monthly totals of IMERG, CFSR and GSOM precipitation during 2001-2020

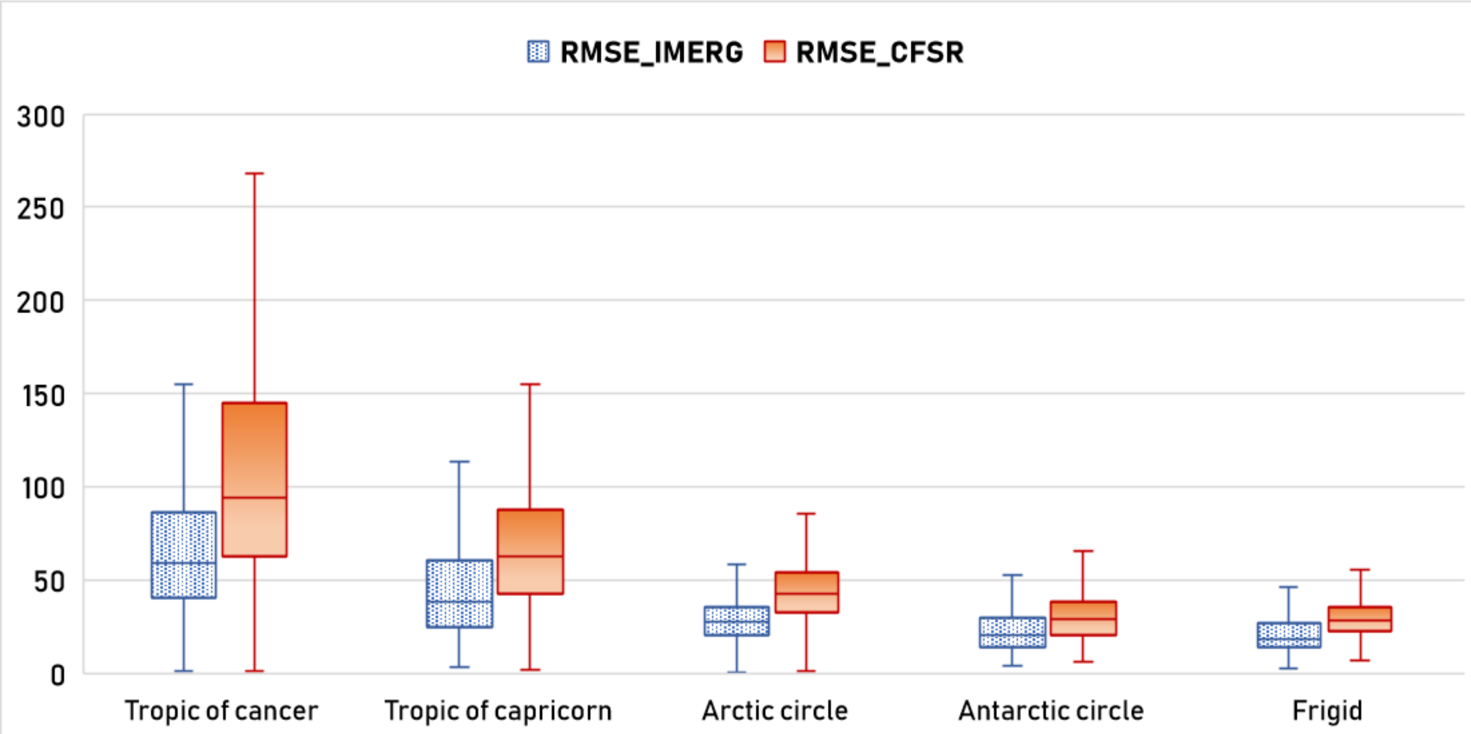

Figure 5

RMSE (mm) computed using monthly information of IMERG, CFSR and GSOM precipitation during 2001-2020

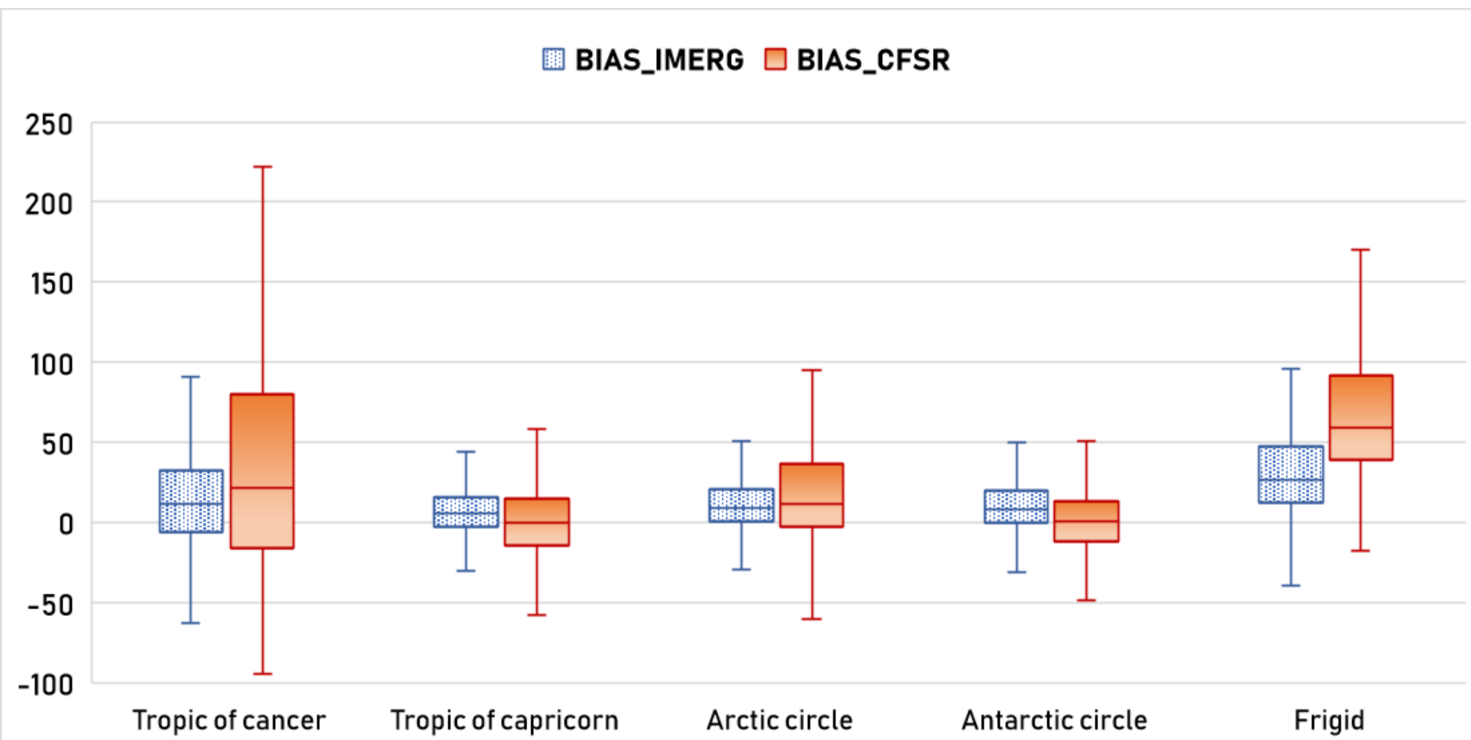

Figure 6

Biases (%) computed using monthly information of IMERG, CFSR and GSOM precipitation during 2001-2020

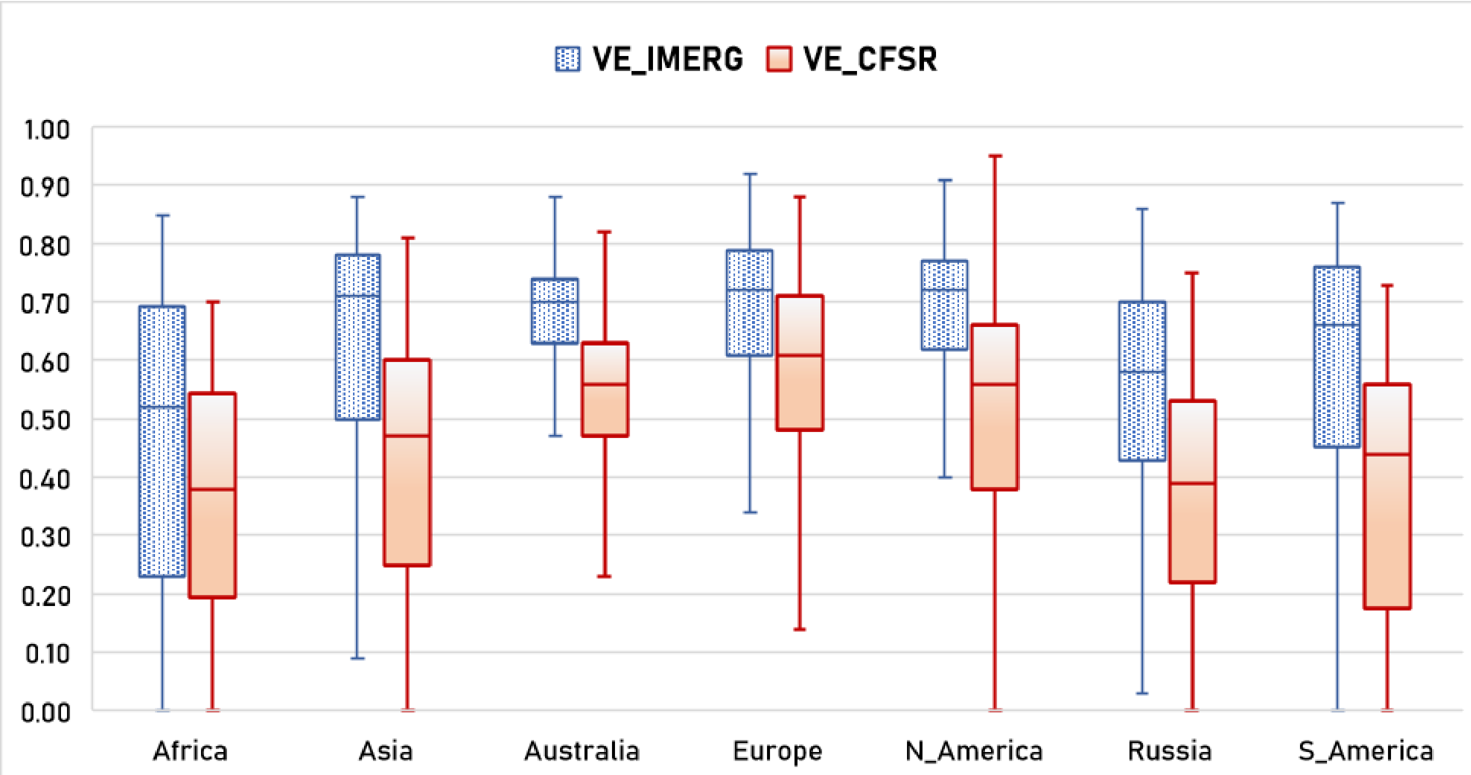

Figure 7

VE values computed for each continent by comparing IMERG (CFSR) and GSOM precipitation during 2001-2020

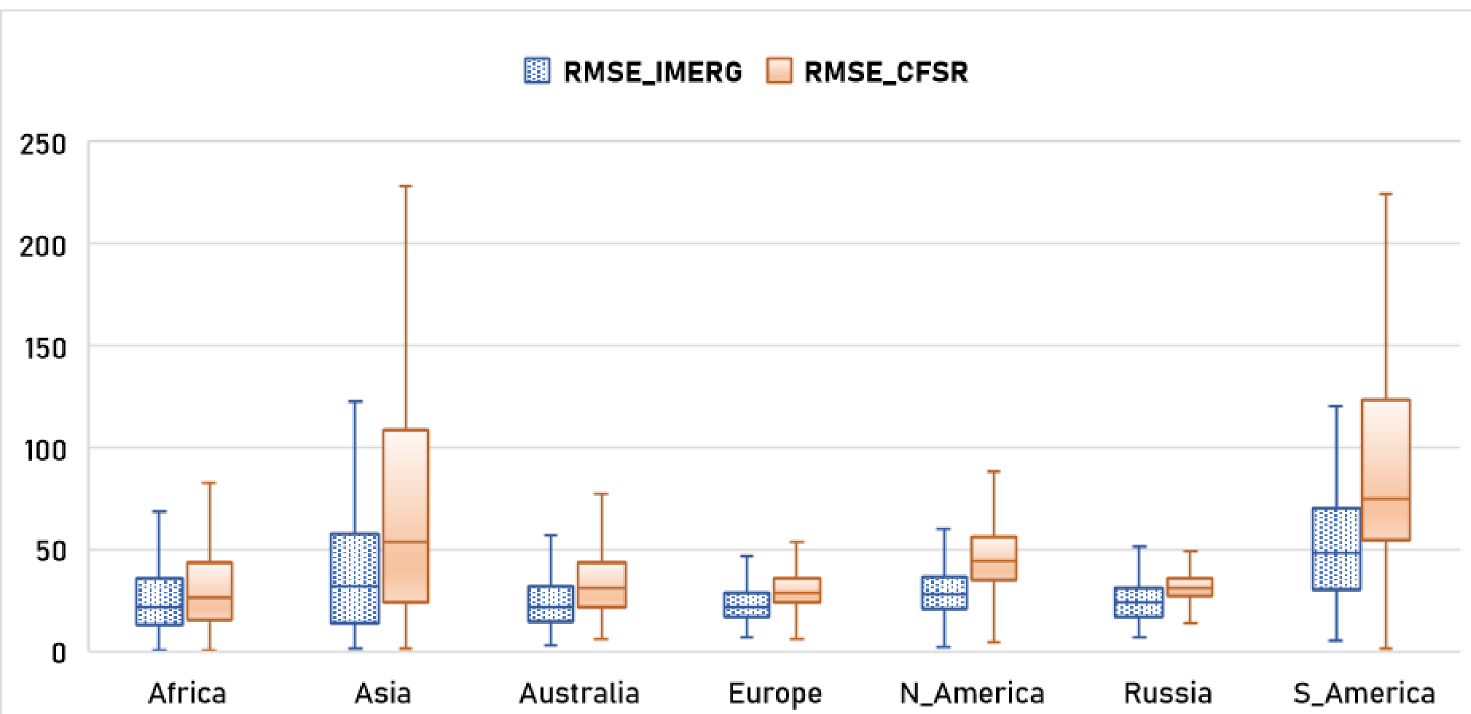

Figure 8

Mean monthly RMSE (mm) values computed using IMERG (CFSR) and GSOM precipitation during 2001-2020

Figure 9

Median NSE values computed for each country by comparing IMERG and CFSR with GSOM precipitation during 2001-2020

Figure 10

Median RMSE values(mm) computed at country level by comparing IMERG and CFSR with GSOM precipitation stations during 2001-2020

Figure 11

VE computed at station level by comparing IMERG (CFSR) with GSOM precipitation during 2001-2020

Figure 12

RMSE (mm) calculated between IMERG (CFSR) and GSOM precipitation at stations during 2001-2020

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryIMERGpaper.docx
- TableS2detailedlistoftheimplementedstations.xlsx
- SupplementaryTS3Meanofperformancemetrices.docx
- TableS4summaryofstatisticsatcountrylevel.xlsx
- TableS5statisticsatstationlevels.xlsx