Jurnal Ilmu Fisika (JIF)
Vol. 14, No. 1, March 2022, pp. 10–20
ISSN: 1979-4657 (Print); 2614-7386 (Online)
https://doi.org/10.25077/jif.14.1.10-20.2022

Jurnal Ilmu Fisika
Open Access

Statistical Comparison of IMERG Precipitation Products with Optical Rain Gauge Observations over Kototabang, Indonesia

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Article Info

Article History:

Received November 24, 2021
Revised November 27, 2021
Accepted November 28, 2021

Keywords:

IMERG-F
Optical rain gauge
GPM
Kototabang
Indonesia

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ABSTRACT

Satellite-based precipitation estimates play a crucial role in many hydrological and numerical weather models, especially to overcome the scarcity of rain gauge data. Globally gridded rainfall product from Integrated Multi-Satellite Retrievals for Global Precipitation Measurement (GPM) (IMERG) has been used in a wide range of hydrological applications. However, the IMERG is inherently prone to errors and biases. This study evaluated the performance of the IMERG-Final run (IMERG-F) product to estimate rainfall in a mountainous area of Sumatra. Validation was carried out using optical rain gauge (ORG) data for 15 years (2002-2016), at Kototabang, West Sumatra, Indonesia. In general, IMERG-F overestimated rainfall in all time scales. The longer the time scale was, the better the performance of IMERG-F we obtained. This feature was indicated by all quantities of continuous and categorical statistical matrices used. The performance of IMERG-F was lower than in other areas of the Maritime Continent, except for the probability of detection (POD) value. IMERG-F could detect rain very well, including for daily and hourly data, but the false alarm rate (FAR) was also relatively high. Such high FAR value may indicate a significant small-scale spatial rainfall variability in mountainous area of Sumatra.

1. INTRODUCTION

Rainfall data are the primary input in climate, meteorological and hydrological modeling (Ning et al., 2017; Mahmoud et al., 2021). These data are also valuable for mitigation of the hydrological disasters (Sharifi et al., 2018) and for managing water sources (Skofronick-Jackson et al., 2017). The high spatial and temporal variation of rainfall makes accurate rainfall measurements still a challenge for many applications.

In general, there are several instruments to measure rainfall: surface-based instruments, including rain gauge and weather radar, and satellite-based instruments. Rain gauge measures rainfall directly, so it is the most accurate rainfall measurement. However, rain gauge observations are limited to a certain point, so they cannot represent a large area (Mahmoud et al., 2018) unless the rain gauge is installed at many points with high density of observation . On the other hand, weather radar has a broader observation coverage than rain gauge (Tang et al., 2016), but the number of weather radars is still limited in developing countries, including Indonesia (Hou et al., 2014; Marzuki et al., 2018). Based on the above conditions, the use of rain data from satellite products is an option.

Among the satellites that can provide information related to rainfall is the Tropical Rainfall Measuring Mission (TRMM). The United States National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA) launched the TRMM satellite in 1997 (Skofronick-Jackson et al., 2017). Since 2015, TRMM has been replaced by the Global Precipitation Measurement (GPM). In general GPM principle is the derivation of the TRMM, but GPM is equipped with two additional sensors, namely Dual-frequency Precipitation Radar (DPR) and GPM Microwave Imager (GMI), which can improve the observations of drizzle and snow (Hou et al., 2014; Skofronick-Jackson et al., 2017). In addition, GPM also consists of a core observatory (CO) satellite that works together with several sensors from other satellites such as Passive Microwaves (PMW) and Infrared (IR). The combination of these satellites produces rainfall data called Integrated Multi-satellitE Retrievals for GPM (IMERG).

IMERG provides data with a spatial resolution of 0.1° and a temporal resolution of 30 minutes, better than TRMM (Tan & Santo, 2018). IMERG product data are also available in three different observation times, namely early (IMERG-E), late (IMERG-L), and final run (IMERG-F). The IMERG-E, IMERG-L, and IMERG-F are released around 4 hours, 14 hours, and 2.5-3 months after the nominal observation time, respectively (Mahmoud et al., 2019). Although satellite-based rainfall measurement has advantages in area coverage, it also has some limitations (Khodadoust Siuki et al., 2017). Therefore, evaluation of rainfall data from satellites products is needed to understand accuracy and identify the source of the error. Furthermore, the assessment of satellite products is critical before the data is used in hydrological modeling in a particular area (Dembélé & Zwart, 2016).

Validation of IMERG precipitation product in Indonesia is limited to specific locations, such as in eastern Indonesia, by utilizing rain observation stations in Surabaya (Azka et al., 2018), several stations in West Papua (Faisol et al., 2019), and other areas. The lack of information regarding the validation of IMERG data in other regions in Indonesia prompted this research to be carried out. This study evaluated the accuracy of IMERG data by utilizing optical rain gauge (ORG) data at Koto Tabang, West Sumatra, Indonesia. Kototabang is located in mountainous areas of Sumatra, with an elevation of 865 m above sea level (Marzuki et al., 2009). Validation of IMERG data in mountainous areas is often complex due to the lack of rain gauges in these areas (Marzuki et al., 2021a). Therefore, the results of this study will be an essential reference regarding the accuracy of IMERG data in mountainous areas, especially in Sumatra.

2. METHOD

2.1 Data

The rain gauge data used in this study is ORG data installed in Kototabang, West Sumatra, Indonesia (100.32°E, 0.20°S). Sumatra's topography and the position of Kototabang can be seen in Figure 1. ORG works with optical scintillation, a more detailed explanation can be seen on the company's website (OSI, n.d.). The ORG data in Kototabang has a resolution of one minute with an observation period from 2002 to 2016. This is one of the advantages of this study compared to others because most previous research used rain gauge data with a lower temporal resolution, such as daily (Liu et al., 2020). Better temporal resolution can ensure better data quality for longer integration time (daily, monthly, and yearly). The IMERG data to be validated is the final run product version 06 (IMERG-F V06). While there are three data types of IMERG data, IMERG-F is recommended for research purposes and weather forecasting, slope monitoring, and hydrological modeling (Sungmin et al., 2017). The IMERG-F has several data types: PrecipiotationCal (with rain gauge calibration) and PrecipitationUnCal (without rain gauge calibration). This study used data of the PrecipitationCal type because the quality is better in measuring surface rainfall (Huffman et al., 2019). The temporal resolution of the IMERG is 30 minutes, and the spatial resolution is 0.1° or equivalent to 11.1 km. This data was downloaded from the NASA website (https://disc.gsfc.nasa.gov/). The ORG and IMERG-F data were downscaled to hourly, daily, monthly, and yearly data for validation purposes. Only rain with intensity ≥ 0.1 mm/h was used in this study.

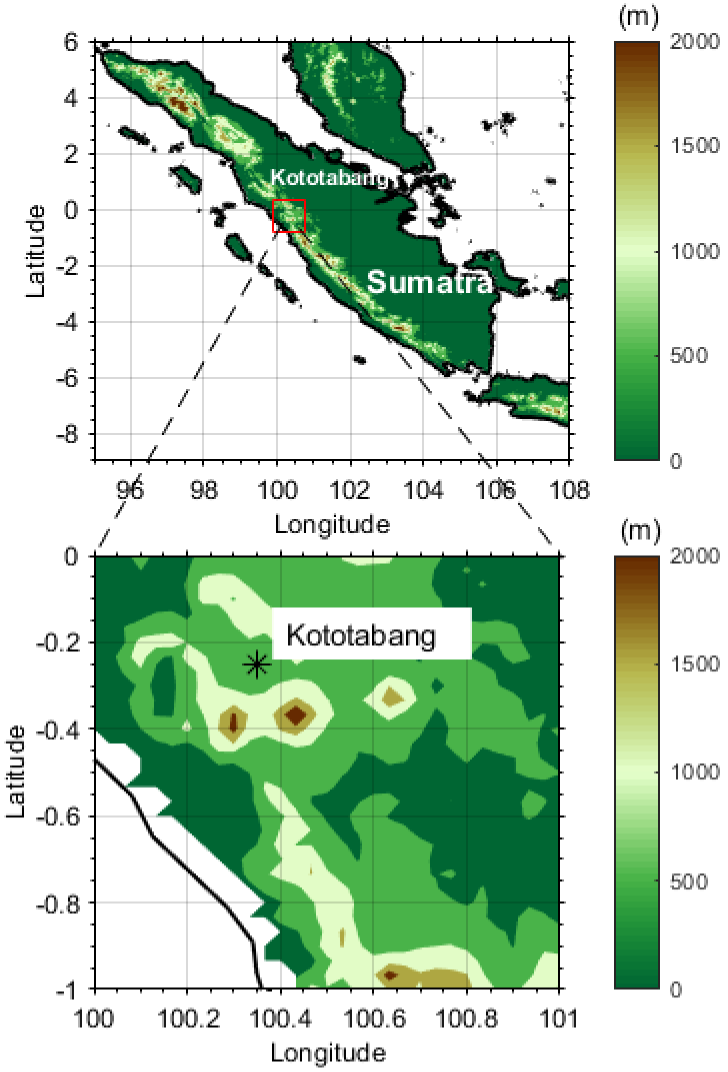


Figure 1. (a) Topography of Sumatra and (b) an enlargement of the square area in panel (a).Symbol * indicates the location of ORG.

2.2 Evaluation Method

IMERG performance is evaluated with two forecasting tests: general assessment (continuous statistical matrices) and precipitation detection capability (categorical statistical matrices). Forecasting tests are carried out for monthly, seasonal, daily, and hourly data. Both instruments are considered to be observing rain if the value of the hourly rainfall intensity is more than 0.1 mm/h. Meanwhile, for daily and monthly data, a threshold of 1 mm is used. Continuous statistical matrices tests used are Pearson Correlation Coefficient (CC), Root Mean Square Error (RMSE), and Relative Bias (RB) (Table 1). The CC parameter describes the rate of linear correlation between IMERG and ORG. The CC value ranges between -1 (negative correlation) and 1 (positive correlation), and CC of 0 indicates no correlation between the IMERG and ORG data. The RMSE describes the average error magnitude of the IMERG measurement. The smaller the RMSE value (towards 0) is, the smaller the error rate of the IMERG measurement we obtain. Meanwhile, RB describes a systematic bias from IMERG observations, where positive RB indicates that the IMERG overestimates rainfall and vice versa.

Categorical statistical matrices consist of probability of detection (POD), false alarm ratio (FAR), critical succession index (CSI), and Hansen and Kuiper score (HKS). These matrices have a range of values between 0 and 1 (Table 1). POD describes a measure of proportion of ORG rain events successfully detected by the IMERG, while FAR shows proportional measure of the IMERG's tendency to detect rain where none was observed by ORG. Furthermore, CSI or threat score (TS) shows how the IMERG observed rain events (yes event) corresponded to the ORG observed rain events (yes event). Meanwhile, HKS skill score shows how well the IMERG separate the yes events from the no events (Uysal et al., 2021). The perfect score of POD, CSI and HKS is 1 and the perfect score of FAR is 0.

Table 1 Equations of the statistical measures to examine the performance of IMERG-F. *N* denotes the number of data, G_i indicates rain gauge data and S_i is satellite rain product, σ_G and σ_S are standard deviation of rain-gauge and satellite precipitation, respectively. Every satellite gauge match-up can be classified as a hit (H, observed rain correctly detected), a miss (M, observed rain not detected), a false alarm (F, rain detected but not observed) events.

Performance measure	Equation	Perfect value
CC	$\frac{\sum_{i=1}^{n}(S_i-\bar{S})(G_i-\bar{G})}{\sqrt{\sum_{i=1}^{n}(S_i-\bar{S})^2(G_i-\bar{G})^2}}$	1
RMSE	$\sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i-G_i)^2}$	0
Relative Bias (RB)	$\frac{\sum_{i=1}^{n}(S_i-G_i)}{\sum_{i=1}^{n}G_i}$	0
POD	H/(H+M)	1
FAR	F/(H+ F)	0
BIAS	(H+F)/(H+M)	1
CSI	H/(H+F+M)	1
HKS	H/(H+M)-F/(F+T)	1

3. RESULTS AND DISCUSSION

3.1 Annual Assessment

Figure 2a shows the comparison between annual rainfall from IMERG-F and ORG. The data percentage for each year varies (Figure 2b) due to the blackout in Kototabang and instrument problems. However, only a few years of observation where data availability was less than 90%, namely 2002, 2006, 2007, and 2012 while the data availability was 90% in other years. IMERG-F overestimates the annual rainfall in Kototabang. This difference is the actual performance of IMERG and is not caused by differences in the availability of observational data. In 2003, 2005, 2008, and 2014, the availability of ORG data was 95% (Figure 2b), but the difference between the annual rainfall between IMERG-F and ORG was also huge (Figure 2a). Taking the year for which data availability is > 90%, the mean annual rainfall from ORG and IMERG observations in Kototabang is 2404.76 mm and 3132.12 mm, respectively. During 2002 and 2007, the percentage of ORG data is relatively small because there has been no observation of ORG for two months due to instrument problems (Marzuki et al., 2016). The high overestimation of the IMERG-F data for annual rainfall is due to the overestimation of IMERG-F for light and medium rains. IMERG-F underestimates rainfall at very low intensity and extreme rainfall

(Ramadhan et al., 2022). Such overestimation of annual rainfall by IMERG data was also found in Singapore (Tan & Duan, 2017).

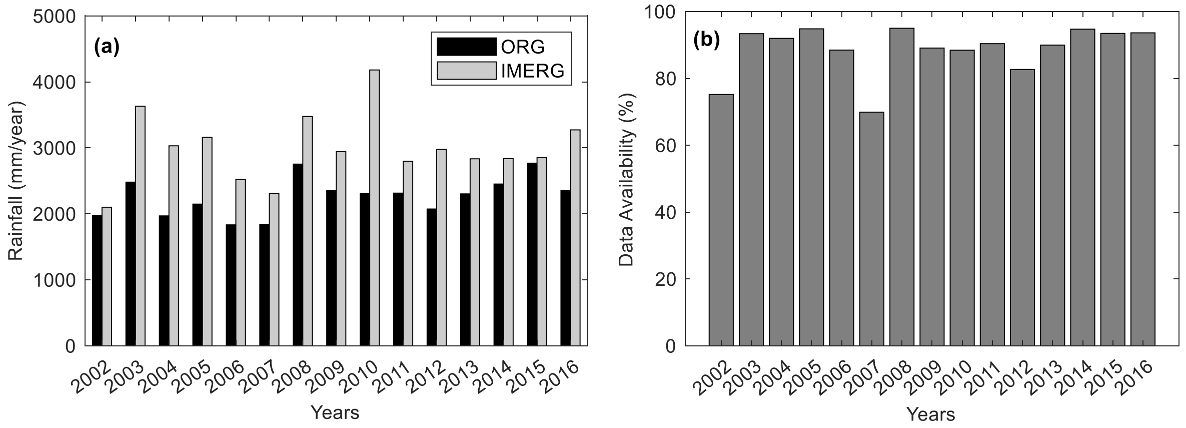


Figure 2 Comparison between annual rainfall from IMERG and ORG observation (a), and data availability of ORG observation (b). Data availability is calculated from recorded-to-total time ratio for every year. Because the data resolution is one minute, the total observation time in one day is 1440.

3.2 Monthly, Daily, and Hourly Assessments

General assessment and precipitation detection capability were used to evaluate daily and hourly data, while only a general assessment was carried out for monthly data because IMERG-F has an excellent ability to detect monthly rain events (Liu et al., 2020). For daily and hourly assessments, we used the ORG data with the availability of 100%, while for monthly data, we used the data with more than 90%. Like annual data, it is challenging to get ORGs operating 100% of time for each month. Figure 3 shows average monthly rainfall from IMERG-F and ORG along with the data percentage for each month. With the availability threshold > 90%, we obtained 121 monthly data that meet these requirements. The least amount of monthly data is observed for January and March (8 data). In general, IMERG-F can capture monthly rainfall patterns in Kototabang (Figure 3a). Monthly rainfall in Kototabang has two peaks of rainfall, namely in April and November, consistent with some previous studies (Marzuki et al., 2013b, 2013a, 2016, 2021c). The peak of rainfall in Kototabang is influenced by the Asian Monsoon and local convection (Kozu et al., 2006; Marzuki et al., 2021c).

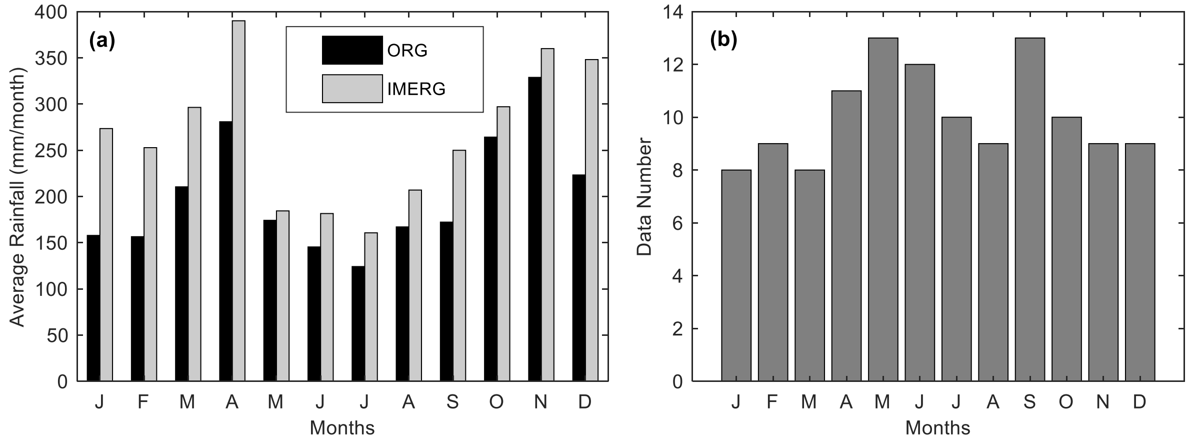


Figure 3 Comparison between average monthly rainfall from IMERG-F and ORG observation (a), and data number of ORG observation for each month (b).

Figure 4 shows the scatter plot of monthly, daily, and hourly rainfall from ORG and IMERG observations. The average monthly, daily, and hourly rainfall in Kototabang from ORG (IMERG-F) was 198.74 (262.48) mm/month, 6.73 (8.58) mm/day, and 0.29 (0.37) mm/h, respectively. In general, the longer the rainfall observation time scale, the better the accuracy of IMERG observations, which can be seen from the CC value. The CC value for monthly, daily, and hourly data is 0.57, 0.47, and 0.25. Liu et al. (2020) found a higher monthly CC value (0.72) for Bali. In addition, Tan et al. (2017) also found a better monthly CC in Singapore (0.82). The same condition was also found in Malaysia, with a CC of 0.78. This result confirms several previous studies where IMERG observations are strongly influenced by topographic conditions (Xu et al., 2019). The Kototabang area is located in a mountainous area (Figure 1) so that the CC value is lower than other previous studies (Figure 4a).

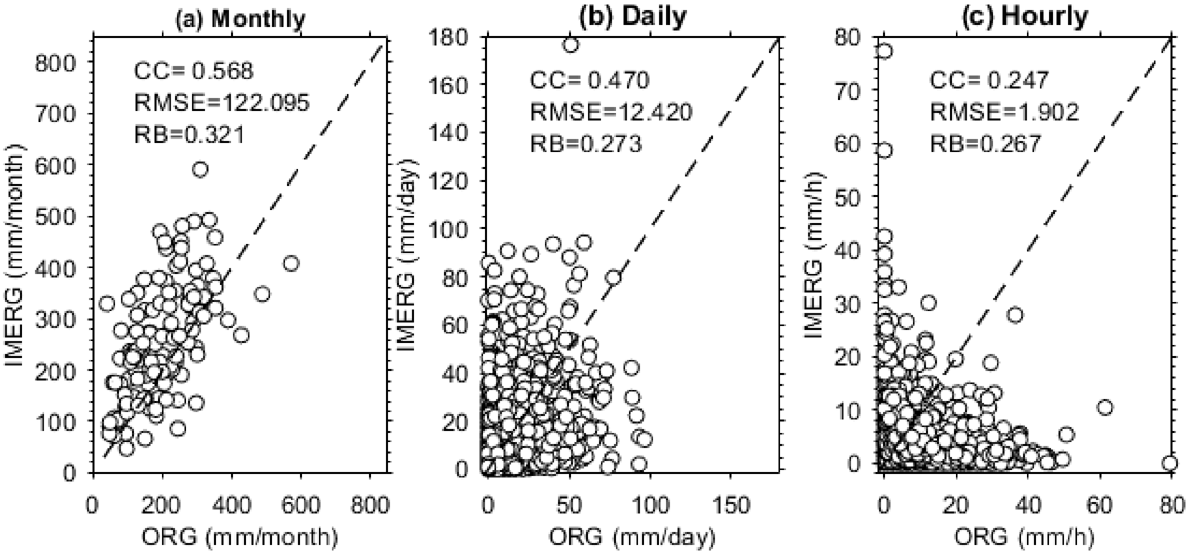


Figure 4 Scatter plot of monthly (a), daily (b), and hourly (c) rainfalls from ORG and IMERG observations.

Overall, IMERG overestimates monthly, daily, and hourly rainfall as seen from the positive RB value (Figure 4), ranging from 0.27-0.32. For monthly data, these overestimates can also be seen in Figure 3. Monthly RMSE from IMERG and ORG data in Kototabang (122.10 mm/month) is lower than that found in Bali (136.60 mm/month) based on automatic rain gauge (ARG) observations (Liu et al., 2020). However, the monthly RMSE in Kototabang is higher than in Singapore (54.75 mm/month) (Tan & Duan, 2017). The same condition is also found for daily data. Singapore's CC, RMSE, and RB values ranged from 0.53-0.63, 9.86-11.83 mm/day, and -8.58-21.19%, respectively. Although, in general, IMERG-F overestimates daily rainfall, some underestimates can also be seen from Figure 3, as also found in Singapore (Tan & Duan, 2017).

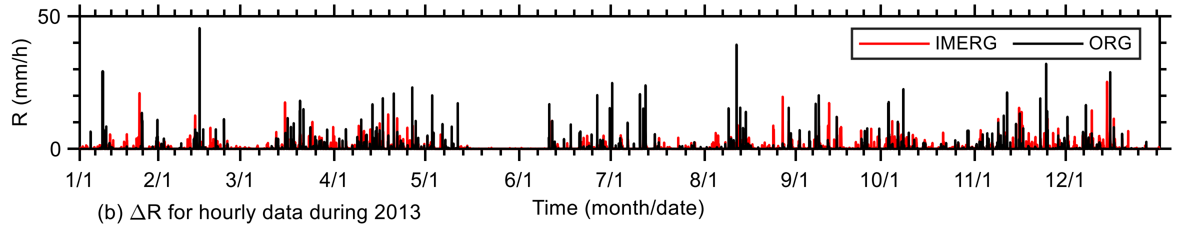
Table 2. Error analyses for daily and hourly IMERG-F products vs. ORG measurements.

Performance measure	Daily	Hourly
POD	0.9187	0.7357
FAR	0.3765	0.7041
CSI	0.5909	0.2675
HKS	0.3493	0.5052

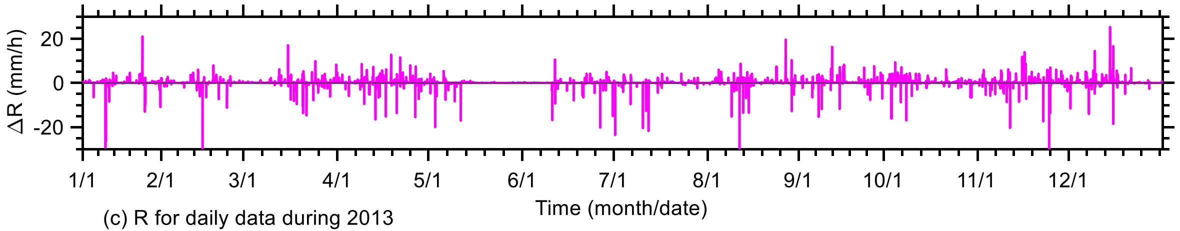
The precipitation detection capability test for daily and hourly rainfall shows that the performance of IMERG is quite good, especially for daily rain (Table 2). The POD and CSI values for daily data were excellent, namely 0.92 and 0.59, with low FAR (0.38). Thus, about 92% of observed rain events by ORG were correctly detected by IMERG-F. The daily POD values in Kototabang were better than those found in Singapore (0.74-0.81), but Singapore's CSI and FAR values were better than

Kototabang. In Malaysia, the daily rainfall POD is also lower (0.89) than that found in Kototabang, but the CSI is better (0.73), and the FAR is lower (0.18) (Tan & Santo, 2018). Meanwhile, in Bali, POD, CSI, and FAR are 0.84, 0.44, and 0.54, respectively (Liu et al., 2020). The lower CSI value in Kototabang is due to the relatively high FAR value. Thus, in Kototabang, the percentage of IMERG-F incorrectly detecting rain is still high.

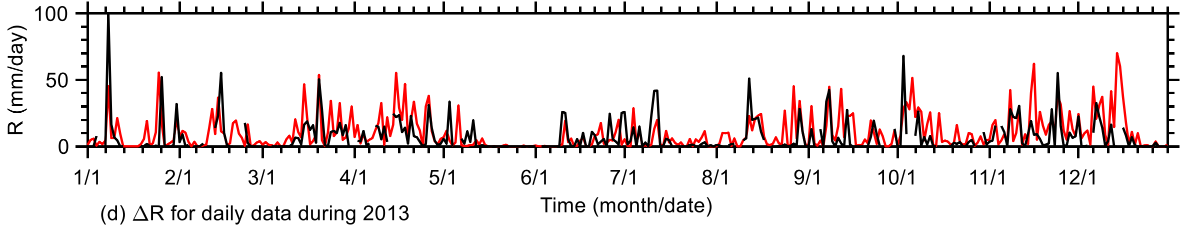
(a) R for hourly data during 2013



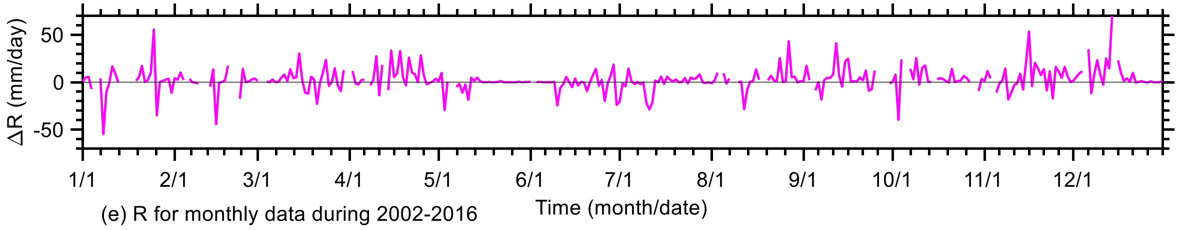
(b) ΔR for hourly data during 2013



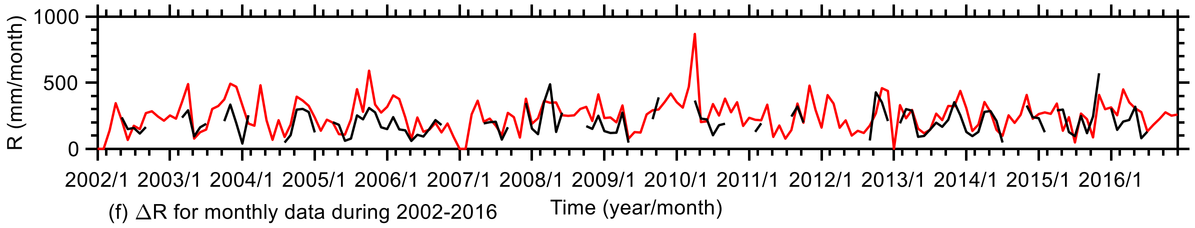
(c) R for daily data during 2013



(d) ΔR for daily data during 2013



(e) R for monthly data during 2002-2016



(f) ΔR for monthly data during 2002-2016

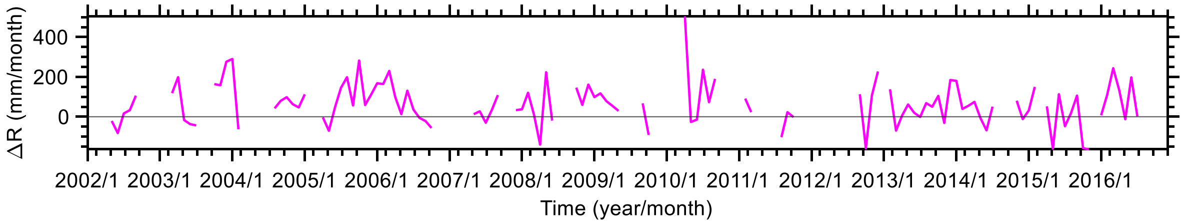


Figure 5 Hourly (a), daily (c) and monthly (e) rainfall from IMERG-F and ORG, and the difference between the two (b, d, f). The value of Δ*R* was calculated by subtracting the rainfall from IMERG with the rainfall from ORG. Positive value of Δ*R* (> 0) indicates IMERG-F overestimates rainfall and vice versa.

There are few references related to IMERG validation for hourly data, epecially in the Maritime Continent. The CC value for hourly data in Kototabang is lower than that found in Guangdong, China (0.35). In contrast, the POD, CSI, and FAR values in Guangdong were lower than those found in Kototabang, namely 0.59, 0.32, and 0.59, respectively (Wang et al., 2017). The high POD value indicates that IMERG is quite good at observing hourly rainfall in Kototabang, although also with a significant error in detecting rainfall events (large FAR). This high FAR condition results in a low CSI value (0.27). High IMERG errors in hourly rainfall observations were also found in Canada (Moazami & Najafi, 2021) and Mainland China (Xu et al., 2019).

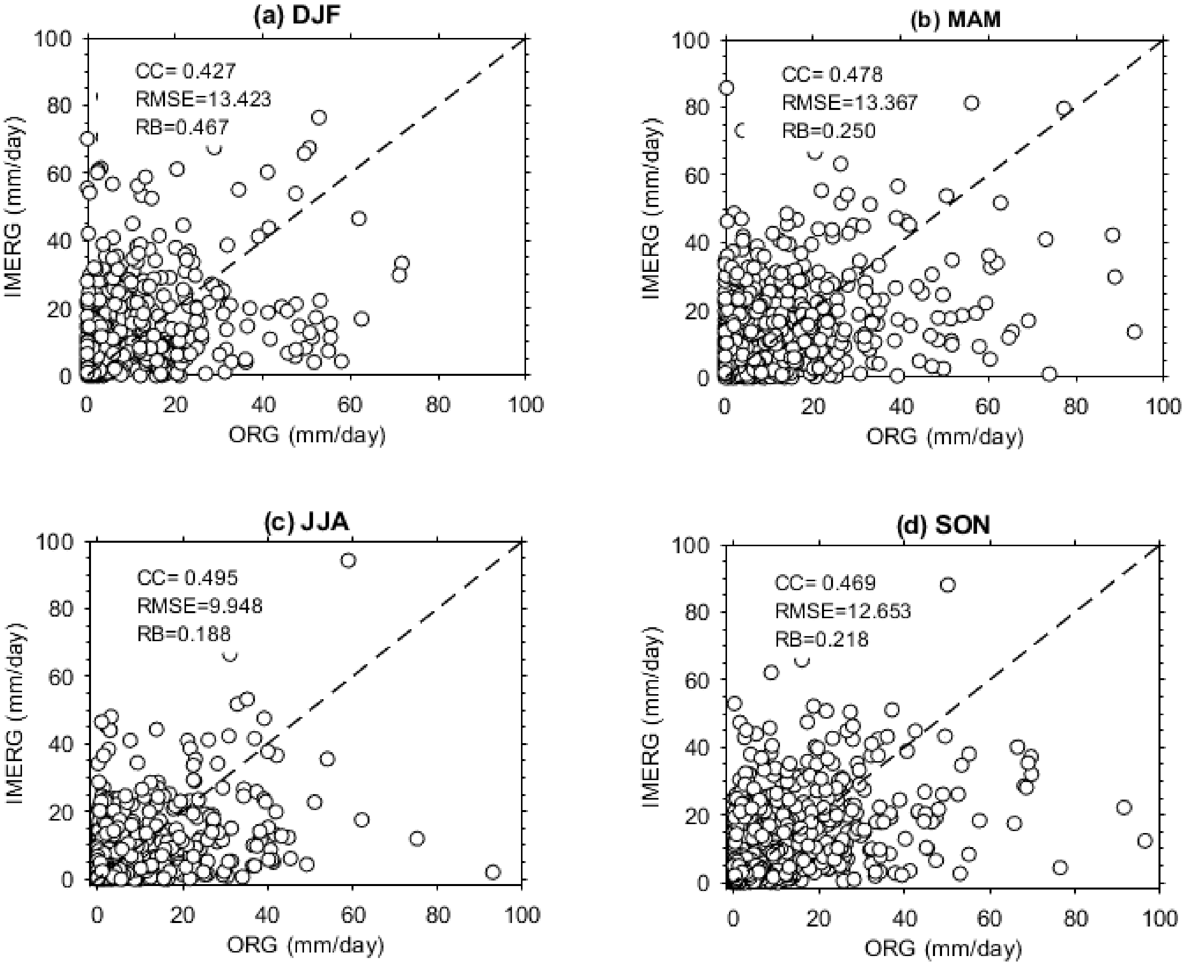


Figure 6. Scatter plot of daily rainfall from ORG and IMERG-F for four different season.

In general, IMERG-F overestimates rainfall in all time scales. However, when we look at the hourly data, IMERG-F sometimes underestimates precipitation, as seen from the data distribution in Figure 4c. To clarify this point, we plot a time series of hourly data during 2013 in Figure 5a. While the IMERG-F captures hourly precipitation's temporal trend, overestimating and underestimating are seen throughout the observations without any particular pattern. Marzuki et al. (2021b) found a time difference of ± 2 hours between the peak time of rain from IMERG and the rain gauge in Sumatra. We tried to shift the IMERG time around ± 2 hours, but the CC value didn't improve. This finding indicates that overestimating and underestimating IMERG observation does not have a specific pattern. This is probably due to the high spatial variation of rainfall in Kototabang in the IMERG data grid (0.1° x 0.1°), which is not sufficiently represented by one observation point. In addition to Mesoscale Convective System (MCS), rain in Kototabang is also often induced by local convection, which causes isolated convective in a small area (Alexander et al., 2006). This condition is likely the reason of the high FAR value in Kototabang. The IMERG-F underestimates very heavy and extreme rains for hourly data

(Figure 5a, b), but on daily and monthly data, IMERG overestimates rainfall. This is likely due to high contribution from the false alarm (precipitation detected by IMERG but not observed by precipitation gauge). In addition, the spatial and temporal variations of daily and monthly rainfall may not be as significant as the hourly rainfall, so that rain gauge and IMERG can capture them better (Figure 5c-f).

3.3 Seasonal Assessments

Figure 6 shows the scatter plot of daily rainfall data for the four seasons. In general, IMERG has a different performance of surface rainfall detection in each season. The highest correlation was found in the JJA season (Figure 6c). This result is consistent with previous research in Bali, which found a better CC during the dry season compared to the rainy season, such as in Bali (Liu et al., 2020), East Asia (Lee et al., 2019), Myanmar (Mohsan et al., 2018), and the Mekong River (Wang et al., 2017). Meanwhile, a low CC was found during the DJF season (Figure 6a). The DJF is the peak month of rainfall in most of the IMC areas, including Kototabang. The low correlation during the wet season may be due to higher rainfall in the tropics (Tan et al., 2018). The ability of IMERG to observe extreme rainfall is very low (underestimate), especially for rain > 50 mm/day (Liu et al., 2020; Ramadhan et al., 2022). Similar to CC, a lower error rate (smaller RMSE) was found during JJA (9.95 mm/day).

The POD value in each season is close to 1 (Table 3), which indicates the high detection ability of IMERG on daily rainfall, as can also be seen in Table 2. The highest POD and CSI values were found during SON, namely 0.95 and 0.66, respectively, consistent with those found in Plain China (Xu et al., 2019). The FAR value for each season is still relatively high, especially during JJA (~0.45). In general. IMERG's performance in detecting daily rainfall in Kototabang during SON is better than in the dry season (JJA). However, the bias during JJA is smaller, which can be seen from the RB value (Figure 6a). In dry months, high rainfall intensity where IMERG does not estimate reasonably (Tan & Santo, 2018), rarely occurs. This condition causes the RMSE and RB values to be smaller.

Table 3 Error analyses for monthly IMERG products vs. ORG measurements, for different seasons.

Performance measure	DJF	MAM	JJA	SON
POD	0.9189	0.9258	0.8695	0.9458
FAR	0.3984	0.3702	0.4476	0.3094
CSI	0.5712	0.5995	0.5101	0.6643

4. CONCLUSION

The results of this study show that the performance of IMERG-F for the mountainous area of Sumatra still needs to be improved. From all the quantities of continuous and categorical statistical matrices used, the performance of IMERG-F in the Sumatra Mountains is lower than in other areas of the Maritime Continent, except for the probability of detection (POD) value. IMERG-F can detect rain very well (high POD value) for daily and hourly data, but the false alarm rate (FAR) is also relatively high. This study confirms the need to improve IMERG's ability to estimate rainfall in mountainous areas of the tropical region, especially Indonesia. In general, IMERG-F overestimated rainfall in all time scales. The longer the time scale, the better the performance of IMERG-F. Therefore, the IMERG-F data for longer timescales such as annual, monthly, and daily data can be used in hydrological and numerical weather models. The current study is still limited to one observation point. The high FAR value found for hourly data may be caused by the inability of one observation point to represent rainfall variations in one IMERG-F grid (0.1° x 0.1°). Therefore, testing with several rain gauge stations in one IMERG-F grid should be carried out to ensure the possible source of high FAR.

ACKNOWLEDGEMENT

This study was supported by 2021 World Class Research Grants from from Ministry of Education and Culture (Contract no: 104/E4.1/AK.04.PT/2021). The Optical Rain Gauge (ORG) was operated and maintained by Kyoto University, Shimane University under collaboration with National Institute of Aeronautics and Space (LAPAN). We also thank National Aeronautics and Space Administration (NASA) for providing IMERG-F data.

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