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Atmospheric Research 244 (2020) 105032

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmosres

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ARTICLE INFO

Keywords:
Assessment
Bali
CHIRPS
GSMaP
IMERG

ABSTRACT

Satellite precipitation product estimates (SPPEs) provide rainfall data on regional and global scales and have the potential to be applied in various fields. Several satellite precipitation estimates are available for their various features in retrieval algorithms, used sensor instrument, spatial–temporal resolution, and coverage area. Global Satellite Mapping of Precipitation (GSMaP), Integrated MultisatellitE Retrievals (IMERG), and Climate Hazards Group Infrared Precipitation with Station (CHIRPS) are global coverage precipitation datasets with high spatial resolution (0.1°–0.05°) and high temporal resolution (from 30 min to daily updates). The objective of this study was to assess the performance of GSMaP, IMERG, and CHIRPS over Bali Island from 2015 to 2017 in terms of ground rain gauge data over high density of rain gauge stations (27 in-situ rain gauges) and at various elevations, rainfall intensities, and temporal scales (i.e., daily, penta-days, monthly, and seasonal). A traditional point-to-pixel-based method along with a new introduced continuous, categorical, and volumetric statistical indices comparison approach were implemented to evaluate satellite products. The assessment results demonstrated that IMERG products achieved the highest performance on daily, penta-day, and seasonal timescales, whereas CHIRPS outperformed the other two products on the monthly time scale. Moreover, IMERG was more efficient in detecting rainfall events at different altitudes, but it tended to overestimate rainfall events at high altitudes. With respect to their abilities to detect rainfall events, GSMaP, IMERG, and CHIRPS tended to underestimate the frequency of light rainfall events (0–1 mm/day) and heavy rainfall events (> 50 mm/day) but overestimate the frequency of moderate rainfall events (5–10 mm/day). Our result not only highlight IMERG products exhibited better performance in comparison to GSMaP and CHIRPS in Bali Island but also recommend that further improvement on the precipitation estimate algorithm is required by considering complex terrain over small island in the maritime continent area.

1. Introduction

Accurate temporal and spatial variability of global rainfall data information has the potential for application in the prediction of extreme weather conditions, climatology, hydrological simulation, agriculture, flood monitoring, drought monitoring, and water resource management (Ummenhofer and England, 2007; Hou et al., 2008; Kucera et al., 2013; Toté et al., 2015; Setiawati et al., 2016; Xu et al., 2017; Ayehu et al., 2018). Rain gauges are the main source of rainfall data obtained through direct measurement (Salio et al., 2015). However, the uneven distribution of rain gauges in remote areas is a crucial challenge to overcome for effective spatial coverage (Feidas et al., 2009). The secondary source of rainfall data is indirect measurement through radar, numerical models, and satellite precipitation product estimates (SPPEs). However, data extracted from indirect measurements must be calibrated and validated (Salio et al., 2015).

SPPEs provide integrated temporal and spatial coverage of rainfall measurements even in remote areas and over oceans (Feidas, 2010). The development of SPPEs began from the use of infrared (IR) thermal geostationary satellites, followed by the use of passive microwave (PMW) sensors, and later the integration of IR and PMW technologies, which is the commonly used approach for estimating rainfall from satellite data (Arkin and Meisner, 1987; Kucera et al., 2013; Ayehu et al., 2018). Various SPPEs are accessible in various spatial resolution (0.25°–0.04°), temporal resolution (monthly–30 min), spatial coverage (global and regional), and temporal coverage (1979–present); some examples are the Tropical Application of Meteorology Using SATellite (TAMSAT; Milford and Dugdale, 1990), Precipitation Estimation from

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https://doi.org/10.1016/j.atmosres.2020.105032
Received 12 January 2020; Received in revised form 5 April 2020; Accepted 8 May 2020
Available online 15 May 2020
0169-8095/

Remotely Sensed Information Using Artificial Neural Networks (PERSIANN; Hsu et al., 1997), Climate Prediction Center Morphing Algorithm (CMORPH; Joyce et al., 2004), Naval Research Laboratory–Blended (NRBL; Turk and Miller, 2005), Global Satellite Mapping of Precipitation (GSMaP; Okamoto et al., 2005), Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA; Huffman et al., 2007), Global Precipitation Measurement (GPM; Hou et al., 2008), the Integrated Merged MultisatellitE Retrievals (IMERG; Hou et al., 2014), African Rainfall Climatology version 2 (ARC 2; Novella and Thiaw, 2013), Climate Hazards Group InfraRed Precipitation with Station (CHIRPS; Funk et al., 2015), Multi-Source Weighted-Ensemble Precipitation (MSWEP; Beck et al., 2017), and the satellite soil moisture observations derived from the European Space Agency (ESA) Climate Change Initiative (SM2RAIN-CCI; Ciabatta et al., 2018).

SPPE techniques are not sufficiently accurate because they involve numerous uncertainties. The uncertainties may arise from sampling time errors, device calibration errors, and errors from the algorithms used (Gebremichael et al., 2005). Such uncertainties affect the accuracy of the SPPE data and limits their use for various study purposes. Accurate validation of data is crucial for verifying the performance of SPPEs so that they can be used in various applications.

Validation, assessment, evaluation, intercomparison, and error analysis of SPPEs in terms of ground rain gauge data have been performed simultaneously with the development of the satellite products (e.g., Huang et al., 2018). Daily and 10-day validation data of TRMM, PERSIANN, CMORPH, and GSMaP in Colombia indicated that PERSIANN and GSMaP exhibit the lowest performance, whereas CMORPH exhibits the highest performance (Dinku et al., 2010). IMERG outperformed TRMM at all spatial scales and altitude ranges in the detection of the accumulation of daily rainfall from May 1, 2014 to October 31, 2014 in the Tibetan Plateau region of China (Xu et al., 2017). CHIRPS products exhibited higher performance than those of TAMSAT and ARC 2 in terms of decadal and monthly analyses and elevation variations in the Upper Blue Nile Basin (Ayehu et al., 2018). CHIRPS yielded more accurate results for rainfall estimation for stations located in lower areas, but less accurate results for high altitudes ($>$ 1000 m) in the Central Andes of Argentina (Rivera et al., 2018). CHIRPS and TMPA exhibited favorable results compared with rain gauges across India and its subregions; MSWEP was second best, but SM2RAIN-CCI largely underestimated rainfall (Prakash, 2019).

In Indonesia, TRMM has been mostly used for the validation of SPPEs. Suseno and Yamada (2011) found that TMPA exhibited higher performance than Multifunctional Transport Satellites (MTSATs) combined with TRMM 2A12 in terms of temporal validation (hourly and 3 hourly), but the combination of MTSAT and TRMM 2A12 exhibited higher performance than TMPA in terms of spatial correlation, as revealed in a categorical analysis of 22 automatic rainfall stations in Java Island in December 2007. Daily, decadal, monthly and seasonal validation of data obtained from the TRMM respect to rain gauge stations in three climate regions of Indonesia, Central Java, and Yogyakarta, that TRMM has a high correlation with respect to ground rain gauge stations and underestimated rainfall during the peak rainy season and in high-altitude regions (Prasetia et al., 2013; Sekaranom et al., 2018; Sofiati and Avia, 2018).

Only two studies have evaluated or validated the performance of SPPEs in Bali. As-syakur et al. (2011) conducted daily and monthly evaluations of TRMM 3B42 and 3B43 products with only three rain stations in a 5-year period (1998–2002) by using descriptive statistics. Rahmawati and Lubczynski (2018) validated CMORPH, PERSIANN, and TRMM products by using descriptive statistics and categorical statistics to assess elevation variations and differences across areas with different climate.

Bali Island which is surrounded by the sea has a varied topography, where the edge is a lowland or beach while the middle part has a higher topography with some hills and mountains. This condition is a local factor that can affect local rainfall conditions. Rainfall is the most important input in hydrological modeling which will be used in the evaluation of water resources management (Ayehu et al., 2018), so that there is a need for satellite rainfall products for Bali Island to complement the existing rain gauge station network system, which currently has a high density of around 3/600 km^2. The main contribution of the present study is the assessment of the performance of different high-resolution SPPEs (GSMaP, IMERG, and CHIRPS) over Bali Island with respect to ground rain gauge data over a high density of rain gauge stations and at various elevations, rainfall intensities, and temporal scales (daily, penta-days, monthly, and seasonal) by using three types of statistical analyses (descriptive, categorical, and volumetric indices). The remainder of the paper is organized as follows. Section 2 describes the study area. Section 3 details the data and methodology used in this study. The results and discussion are presented in Section 4, which focuses on the performance of the three SPPEs with respect to temporal intensity, and elevation variations. Finally, Section 5 concludes the paper.

2. Study area

The study region was located in Bali Island, Indonesia, between 8.06°S and 8.85°S and between 114.43°E and 115.71°E, with a total area of 5636.66 km^2 (Fig. 1). Bali has a tropical climate, and seasonal changes are influenced by the monsoon winds that change every 6 months. Bali experiences a wet season from November until April and a dry season from May to October; this is the same seasonal pattern as in Indonesia in general (Aldrian et al., 2003). Based on the 2015–2017 rain gauge data from Balai Wilayah Sungai Bali-Penida (BWSBP), the average rainfall in Bali was determined to be approximately 180 mm/month; the highest rainfall occurs from December to February, whereas the lowest rainfall occurs from July to August. Bali also exhibits variation in the elevation of the terrain from sea surface level, ranging from 0 to 3025 m.

3. Data and methods

3.1. Data

Data from various datasets can be categorized into two types. The first type is conventional observational data, which are obtained from surface rain gauges. The other type is precipitation information, which is estimated from satellite observation. The following subsections describe the background information concerning rain gauge data and satellite observation used in this study.

3.1.1. Rain gauge data

The daily rainfall data were obtained from the BWSBP Ministry of Public Works and Human Settlements of Indonesia. The ministry maintains 44 rainfall and climate stations. Due to some technical breakdowns, only 27 rain gauges were functional for the complete 3-year time series from 2015 to 2017 for daily observation. The selected gauges were distributed over 21 GSMaP and IMERG grid boxes and 27 CHIRPS grid boxes, with each grid box containing at least one rain gauge (Fig. 1). The density of the rain gauge network was 27 gauges per 5633 km^2, which is three times higher than the minimum density standard recommended by the World Meteorological Organization for flat areas in the temperate, Mediterranean, and tropical zones (recommendation: one gauge per 600–900 km^2).

3.1.2. GSMaP

The GSMaP project was begun by a Japanese team of scientists working under the authority of the Japan Science and Technology Agency from 2002 to 2007, and the project was extended by the Japan Aerospace Exploration Agency (JAXA). The GSMaP provides global precipitation products from microwave radiometers at a low Earth orbit and from infrared radiometers on geostationary satellites. The GSMaP

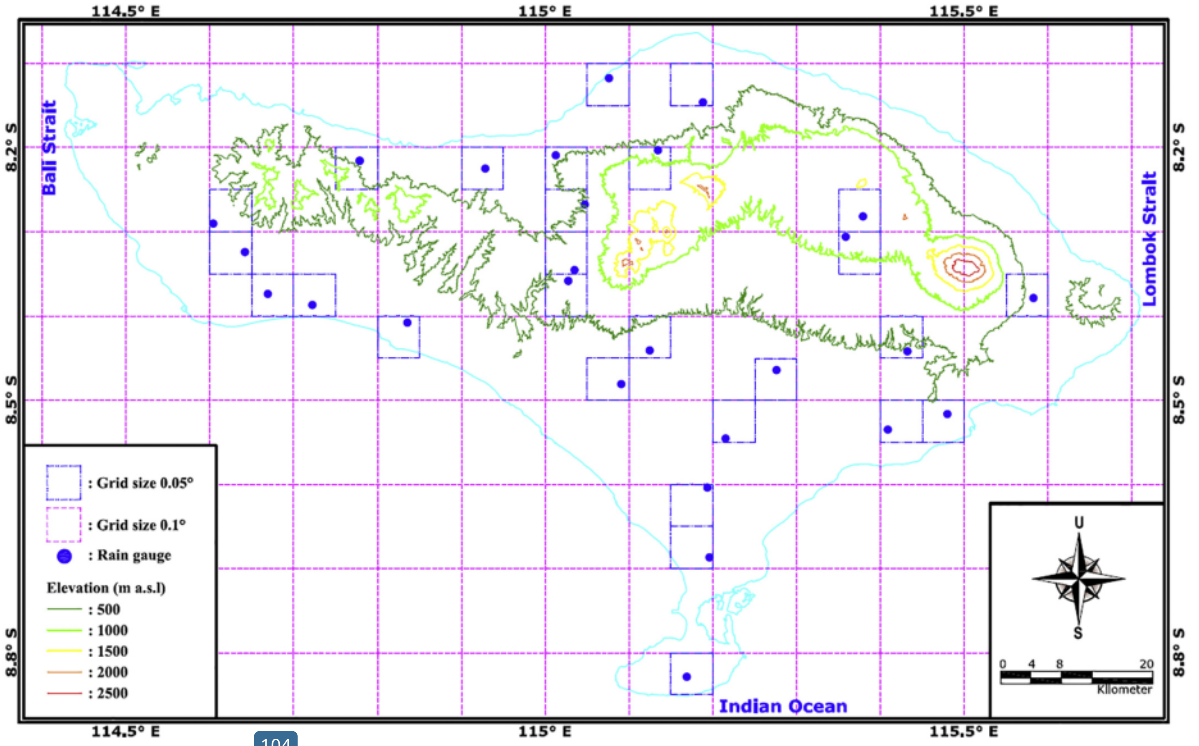

Fig. 1. Map of Bali Island including the location of the rain gauge stations (blue dots), elevation, and selected local gauge domains based on a grid size of 0.1° (purple dashed lines) and 0.05° (blue dashed-double-dotted lines). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

products were generated in near real time with an hourly temporal resolution, spatial resolution of 0.1°, worldwide coverage (60°N to 60°S), and data availability from 2000 to present (Kubota et al., 2007; Ushio et al., 2009). The present study considered the recent version of the GSMaP product (GSMaP_MVK V7) for comparison with other products. Daily GSMaP data can be downloaded from the JAXA website (ftp://hokusai.eorc.jaxa.jp/standard/v7/).

3.1.3. IMERG

The IMERG product is a continuation of TMPA, organized by the National Aeronautics and Space Administration (NASA) and JAXA to supply the next generation of precipitation products at a spatial resolution of 0.1° and a half-hourly temporal resolution (Hou et al., 2014). Its system combines all available microwave precipitation estimates, microwave-calibrated IR estimates, ground gauge analyses, and other possible estimates at fine temporal and spatial scales over the entire globe (Huffman et al., 2018). The IMERG products are categorized into three types, namely early run, late run, and final run, depending on the time of release. The current study used Level-3 IMERG daily data from version V05 of the final run product, following Huang et al. (2018), and the results indicated that this product can accurately depict multiple timescale variations in rainfall in regions with complex terrain such as Taiwan (an island in East Asia) and the current study area of Bali Island (Huang et al., 2018). The spatial and temporal coverage of this product is 60°N–60°S and April 2014–present, respectively. The dataset is made available online at https://pmm.nasa.gov/data-access/downloads/gpm approximately two and a half months after the real-time observations are recorded.

3.1.4. CHIRPS

The CHIRPS dataset was established by the United States Geological Survey and the Climate Hazards Group (CHG) at the University of California with financial support from the United States Agency for International Development (USAID), NASA, and the National Oceanic and Atmospheric Administration. This dataset was primarily developed for the purpose of supporting agricultural drought monitoring where ground rainfall data are rare. CHIRPS has a spatial resolution of 0.05° and has data available on daily, 5-day, 10-day, and monthly temporal resolutions. This product has a global spatial coverage from 50°N to 50°S and temporal coverage from 1981 to the present. The CHIRPS dataset was constructed by combining precipitation estimates obtained from infrared cold cloud duration observations and calibrated with TMPA 3B42 and ground station data from national meteorological agencies (Mexico and countries in Central America, South America, and sub-Saharan Africa) and public and private data archives (Global Historical Climate Network, Southern African Science Service Centre for Climate Change and Adaptive Land Management, Global Summary of the Day, and World Meteorological Organization's Global Telecommunication System). Detailed information regarding the CHIRPS satellite precipitation estimates has been provided by Funk et al. (2015). The spatial resolution of CHIRPS is higher than that of other SPPEs, making it possible to analyze rainfall variations in small areas (Rivera et al., 2018). The present study used the latest version of the dataset (CHIRPS-2.0); this product is available online at ftp://ftp.chg.ucsb.edu/pub/org/chg/products/CHIRPS-2.0/.

3.2. Methods

Point-to-pixel analysis was used to examine the rain gauge observations and the corresponding SPPEs (Fenta et al., 2018). The performance of the SPPEs was assessed on daily, penta-day (i.e., 5-day accumulation), monthly, and seasonal temporal scales by comparing the precipitation estimates with the observations recorded at the 27 rain gauges. Because the IMERG products have only been available since April 2014, the comparison was performed for the period of January 2015 to December 2017. Daily rainfall data were merged to obtain the total penta-day, monthly, and seasonal scale data. Missing data from both rain gauges stations and SPPEs were only a few days so that they were eliminated in the analytic process. Daily rainfall estimates obtained by the SPPEs were assessed as a function of rainfall intensity. Daily rainfall intensities for all ground-based rainfall observations were categorized into the following three groups: 0–1 and 1–5 mm/day (light rain events), 5–10, 10–25, and 25–50 mm/day (moderate rain events), and > 50 mm/day (heavy rain events; Xu et al., 2017). Probability distribution functions (PDFs) were used for graphical comparison of the SPPEs and gauge data. Such evaluation is useful to determine differences in rain intensity measured by a rain gauge and that estimated by satellite pixels (Xu et al., 2017). We divided all the rain gauges in Bali Island into three elevation categories, < 400 m (low altitude), 400–800 m (middle altitude), and 800–1200 m (high altitude), on the basis of the elevation distribution of the rain gauges (Fig. 1). Based on elevation, the number of rain gauge stations distributed at low elevation was 19, middle elevation was 6, and high elevation was 2.

The performance of GSMaP, IMERG, and CHIRPS products were quantitatively analyzed with respect to continuous statistical measurement, categorical metrics, and volumetric indices. The continuous statistics used to measure the difference between satellite estimates and observations included the relative bias (Bias), correlation coefficient (r), mean error (ME), and root mean square error (RMSE). Bias, r, ME, and RMSE values were calculated using the following equation:

$$\mathrm{Bias} = \frac{\sum_{i=1}^{N}(S_i - G_i)}{\sum_{i=1}^{N}(G_i)}, \tag{1}$$

$$r = \frac{\sum_{i=1}^{N}(S_i - \bar{S})(G_i - \bar{G})}{\sqrt{\sum_{i=1}^{N}(S_i - \bar{S})^2}\sqrt{\sum_{i=1}^{N}(G_i - \bar{G})^2}} \tag{2}$$

$$\mathrm{ME} = \frac{1}{N}\sum_{i=1}^{N}(S_i - G_i), \tag{3}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(S_i - G_i)^2}, \tag{4}$$

where S_i represents satellite rainfall estimates, $G_i$is the ground-based rainfall observation, $\bar{S}$ is the average of satellite rainfall estimates, $\bar{G}$ indicates the average of ground-based rainfall observations, N represents the total number of data, and i is the number of the sample.

Bias is the overall deviation of SPPEs from gauge observations, which indicates over- or underestimation. The correlation coefficient describes the degree of linear correspondence between satellite estimates and ground-based observations. The ME describes the average disparity between SPPEs and ground-based observations. RMSE represents the average error between SPPEs and ground measurement. A value of 0 is the deal score for bias, ME, and RMSE, and a value of 1 is the highest correlation coefficient value (Ebert, 2007; Xu et al., 2017).

The categorical metric was used to determine the abilities of satellite products for the occurrence of rainfall scenario. These statistics were extracted from a 2 × 2 contingency table in which the number of hits (H) describes the number of correctly estimated rain events from satellite and ground-based observation, false alarm (F) refers to when rain is estimated but no rain actually occurs, miss (M) refers to when rain is not estimated by the satellite but rain actually occurs, and correct negative (CN) refers to true null events (see Table 1 for details). Three statistical parameters were adopted, namely the probability of detection (POD), false alarm ratio (FAR), and critical success index (CSI). POD score defines the ability of the satellite products to correctly estimate rain events. FAR measures how often the satellite products detect rainfall not confirmed by ground observation. CSI is also known as a threat score and computes the ratio of all events estimated and observed that were correctly diagnosed (Ebert, 2007). The perfect value for POD and CSI is 1, whereas that for FAR is 0. The POD, FAR, and CSI values were examined using the following formulae:

Table 1
Contingency table for categorical metrics.

		Ground-based observation	
		Yes	No
Satellite estimates	Yes	H	F
	No	M	CN

$$\mathrm{POD} = \frac{H}{H + M}, \tag{5}$$

$$\mathrm{FAR} = \frac{F}{H + F}, \tag{6}$$

$$\mathrm{CSI} = \frac{H}{H + M + F} \tag{7}$$

However, the categorical metric does not provide any information on the volume of the variable detected correctly/incorrectly; therefore, this study adopted volumetric indices for the evaluation of data. Volumetric indices provide the volume of the variable of interest detected correctly by SPPEs relative to rain gauge observations (Aghakouchak and Mehran, 2013; Ayehu et al., 2018). In this study, we used the volumetric hit index (VHI), volumetric false alarm ratio (VFAR), and volumetric critical success index (VCSI). VHI is defined as the volume of rainfall accurately detected by SPPEs relative to the volume of the inaccurately detected satellite and missed observations. VFAR can be expressed as the volume of false rainfall detected by the SPPEs relative to the sum of rainfall detected by the SPPEs. VCSI is defined as an overall measure of volumetric performance. VHI, VFAR, and VCSI range from 0 to 1, with the perfect score for VHI and VCSI being 1 and for VFAR, 0. The equations for volumetric indices are as follows:

$$\mathrm{VHI} = \frac{\sum_{i=1}^{N}(S_i \mid (S_i > t \& G_i > t))}{\sum_{i=1}^{N}(S_i \mid (S_i > t \& G_i > t)) + \sum_{i=1}^{N}(G_i \mid (S_i \le t \& G_i > t))}, \tag{8}$$

$$\mathrm{VFAR} = \frac{\sum_{i=1}^{N}(S_i \mid (S_i > t \& G_i \le t))}{\sum_{i=1}^{N}(S_i \mid (S_i > t \& G_i > t)) + \sum_{i=1}^{N}(S_i \mid (S_i > t \& G_i \le t))}, \tag{9}$$

$$\mathrm{VCSI} = \frac{\sum_{i=1}^{N}(S_i \mid (S_i > t \& G_i > t))}{\sum_{i=1}^{N}(S_i \mid (S_i > t \& G_i > t)) + \sum_{i=1}^{N}(G_i \mid (S_i \le t \& G_i > t)) + \sum_{i=1}^{N}(S_i \mid (S_i > t \& G_i \le t))}, \tag{10}$$

where S_i represents satellite rainfall estimates; G_i denotes ground-based rainfall observation; $\bar{S}$ is the average of satellite rainfall estimates; $\bar{G}$ indicates the average of ground-based rainfall observation; N represents the total number of data; i is the number of the sample; and t indicates threshold values of 1 mm/day, 1 mm/5-day, and 1 mm/month for daily, penta-day, and monthly precipitation data segmentation, respectively.

4. Results and discussion

The performance of SPPEs was assessed using continuous statistics (i.e., r, ME, Bias, and RMSE), categorical metrics (i.e., POD, FAR, and

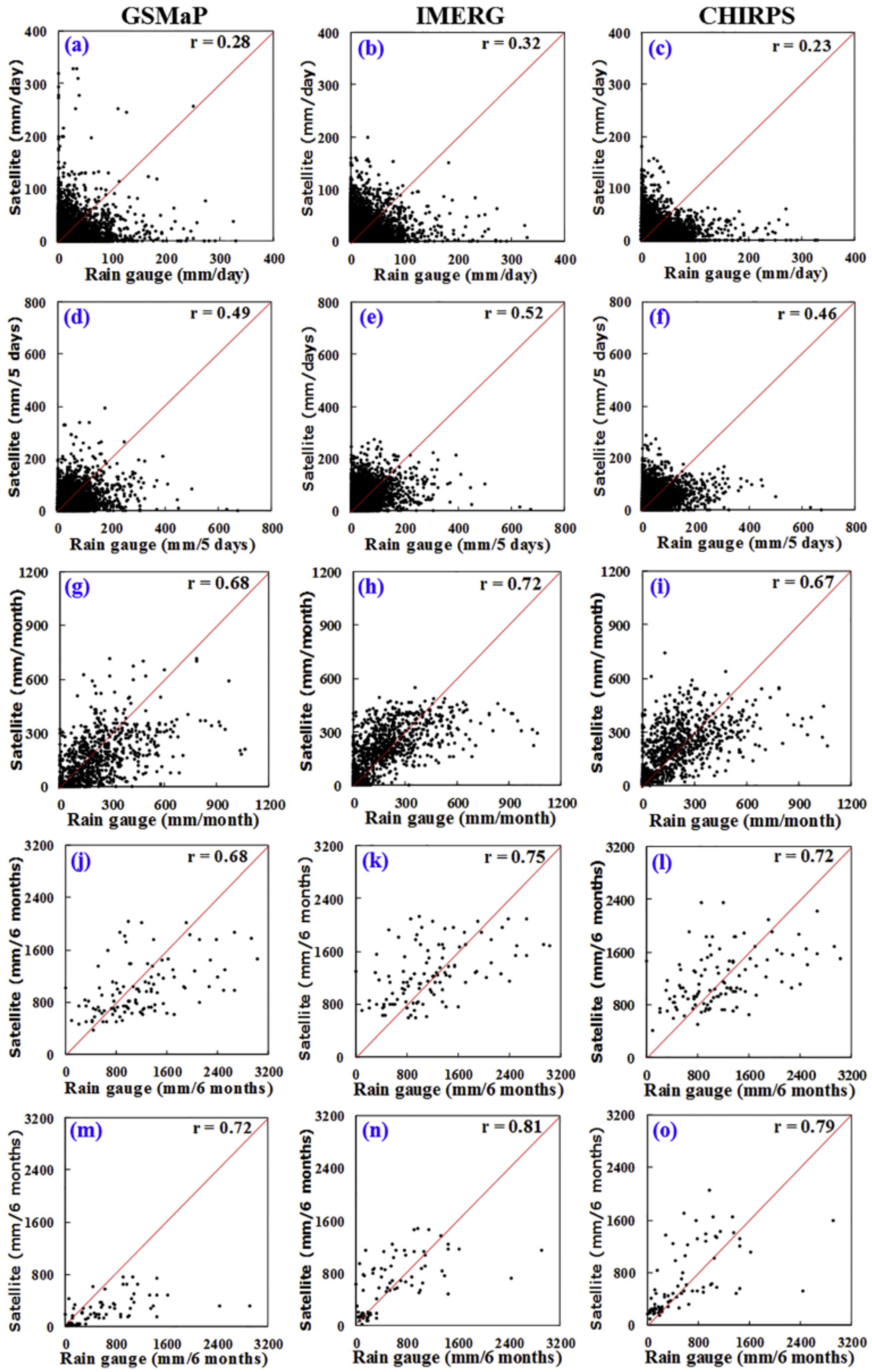

Fig. 2. Scatte[illegible]t of rain gauge observation and satellite estimates (GSMaP, IMERG, and CHIRPS) over Bali Island for the period 2015–2017 at different temporal scales: daily (a, b, c), penta-day (d, e, f), monthly (g, h, i), wet season (j, k, l), and dry season (m, n, o).

CSI), and volumetric indices (i.e., VHI, VFAR, and VCSI) with respect to different time scales (daily, penta-days, monthly, and seasonal), elevations, and rainfall intensities. High values of r, POD, CSI, VHI, and VCSI and small values of ME, Bias, RMSE, FAR, and VFAR indicated good performance of the SPPEs.

4.1. *Performance assessment: temporal variations*

4.1.1. *Daily assessment*

Fig. 2a–c clearly indicates that the three satellite products were poorly correlated with gauge observation data on the daily scale. The daily rainfall satellite product was more vulnerable to errors, probably due to the complexities of Bali Island, namely the diverse topography, nearness of the sea and mountains, and local wind circulation conditions. The diverse topography of Bali Island increases the variability of rainfall (Rahmawati and Lubczynski, 2018). Orographic uplift and blocking can modify rainfall variability, especially in the island area (Lee et al., 2014). The ability of SPPEs is generally not favorable on the daily time scale over complex terrains (Dinku et al., 2010).

In general, IMERG achieved considerably higher performance, with a higher correlation coefficient (r = 0.32), than other products. Both IMERG and CHIRPS products overestimated the overall daily rainfall compared with rain gauges, yielding a positive value for relative bias (0.24, 0.17) and ME (0.44 mm/day and 0.22 mm/day). Nevertheless, GSMaP produced smaller daily rainfall estimates than rain gauges, yielding negative values for relative bias and ME (−0.17 and − 1.62 mm/day). Of the three SPPEs, IMERG was more consistent with gauge observations in terms of most statistical parameters except bias, ME, FAR, and VFAR (Table 2). The POD, CSI, VHI, and VCSI values (0.84, 0.44, 0.72, and 0.41, respectively) of IMERG were higher than those of GSMaP and CHIRPS, even though bias (0.24) and FAR (0.54) values of IMERG were higher than those of both GSMaP and CHIRPS. This might suggest that the high temporal resolution of IMERG in detecting the relative frequency of rain events makes it possible to more efficiently capture the regional variability of daily rainfall (Dezfuli et al., 2017).

The results of categorical and volumetric indices for the three satellite products are presented in Fig. 3a and b. Fig. 3a and b shows a boxplot of categorical and volumetric indices for all the SPPEs based on multistation statistics. The first and third quartiles of the data are shown at the bottom and top of the box plot, and the line beside the box represents the median. The lines at the bottom and top of the whisker represent the minimum and maximum values, respectively, of the data, and any line not between the whiskers denotes an outlier. Fig. 3a and b indicate that IMERG performed better in terms of POD, CSI, and VHI, whereas GSMaP performed better in terms of FAR, VFAR, and VCSI. In the daily assessment, IMERG products exhibited higher performance than the other two SPPEs.

4.1.2. *Penta-day assessment*

The performance of SPPEs was also assessed at 5-day accumulations (penta-days) because research has suggested that the common large-scale circulation period in the target region occurs in penta-days (Crétat et al., 2014). The result is presented in Table 2, and the scatter plots in Fig. 2d–f and Fig. 3c–d. Fig. 2d-f shows a quantitative comparison of the mean penta-day rainfall between rain gauge stations and satellite products across 3 years over Bali Island. Among the three SPPEs, IMERG yielded the highest correlation coefficient (r = 0.52). Table 2 reveals that IMERG also has the highest value of POD (0.93), CSI (0.69), VHI (0.88), and VCSI (0.69), indicating that IMERG detected rainfall on the penta-day scales more efficiently than the other two SPPEs. Moreover, Fig. 3c and d indicate that IMERG exhibited the best performance among the satellite products in detecting rainfall events on the basis of POD, CSI, VHI, and VCSI. IMERG covered a short range of POD and VHI, indicating that the hit estimates achieved high performance.

GSMaP tends to underestimate the rainfall amount with a bias of approximately −17%. The negative bias of GSMaP found in this study is supported by the results of previous studies in Bolivia where GSMaP-v6 yielded a bias value of approximately −22.4% (Satgé et al., 2017). GSMaP also exhibited the lowest RMSE (61.93 mm/5 days), FAR (0.23), and VFAR (0.17) of the three products.

CHIRPS overestimated the penta-day rainfall observed by rain gauges by a bias of 0.17 with an ME of 2.23 mm/5 days. CHIRPS exhibited the lowest correlation coefficient (0.46), POD (0.81), CSI (0.64), VHI (0.81), and VCSI (0.63) among the three products. This result indicates that the performance of CHIRPS products in penta-day analysis was lower than the two other SPPEs.

Statistical analysis indicated that satellite products are sufficiently accurate with respect to ground data at penta-day accumulation (Ebert, 2007). Consistent with Ebert (2007), a comparison of the statistics of penta-day assessment with those of daily assessment in Table 2, Figs. 2 and 3 also shows a clear increase in the correlation coefficient, POD, CSI, VHI, and VCSI and decrease in the FAR and VFAR for all three SPPEs. Most penta-day statistical analyses suggest that IMERG has a more favorable performance in rainfall estimation than GSMaP and CHIRPS products.

4.1.3. *Monthly assessment*

The daily GSMaP, IMERG, and CHIRPS rainfall estimates and rain gauge observations were aggregated to monthly total rainfall. The monthly rainfall dataset has great potential for application in water resources management (water balance analysis). Table 2 presents a

Table 2
Performance assessment of GSMaP, IMERG, and CHIRPS at various time scales.

Time scale	SPPEs	r	Bias	RMSE	ME	POD	FAR	CSI	VHI	VFAR	VCSI
Daily	GSMaP	0.28	−0.17	17.32	−1.62	0.73	0.49	0.43	0.59	0.45	0.39
	IMERG	0.32	0.24	17.19	0.42	0.84	0.54	0.44	0.72	0.51	0.41
	CHIRPS	0.23	0.17	17.56	0.22	0.54	0.49	0.35	0.55	0.52	0.34
Penta-days	GSMaP	0.49	−0.17	61.93	−16.64	0.89	0.23	0.69	0.79	0.17	0.68
	IMERG	0.52	0.24	62.72	4.25	0.93	0.26	0.69	0.88	0.24	0.69
	CHIRPS	0.46	0.17	64.03	2.23	0.81	0.24	0.64	0.81	0.26	0.63
Monthly	GSMaP	0.68	−0.17	145.81	−49.33	0.97	0.09	0.89	0.92	0.06	0.87
	IMERG	0.72	0.24	136.60	12.68	0.98	0.09	0.89	0.97	0.09	0.88
	CHIRPS	0.67	0.17	144.32	6.61	1.00	0.10	0.90	1.00	0.11	0.89
Wet season	GSMaP	0.68	−0.05	527.39	−168.50	1.00	0.01	0.99	1.00	0.01	0.99
	IMERG	0.75	0.20	514.16	95.03	1.00	0.01	0.99	1.00	0.01	0.99
	CHIRPS	0.72	0.13	514.51	22.45	1.00	0.01	0.99	1.00	0.01	0.99
Dry season	GSMaP	0.72	−0.25	471.29	−366.08	1.00	0.01	0.99	1.00	0.01	0.99
	IMERG	0.81	0.82	396.46	26.47	1.00	0.01	0.99	1.00	0.01	0.99
	CHIRPS	0.79	0.70	422.89	50.49	1.00	0.01	0.99	1.00	0.01	0.99

RMSE and ME are presented at the daily (mm/day), penta-days (mm/5 days), monthly (mm/month), and seasonal (mm/6 months) time scales.

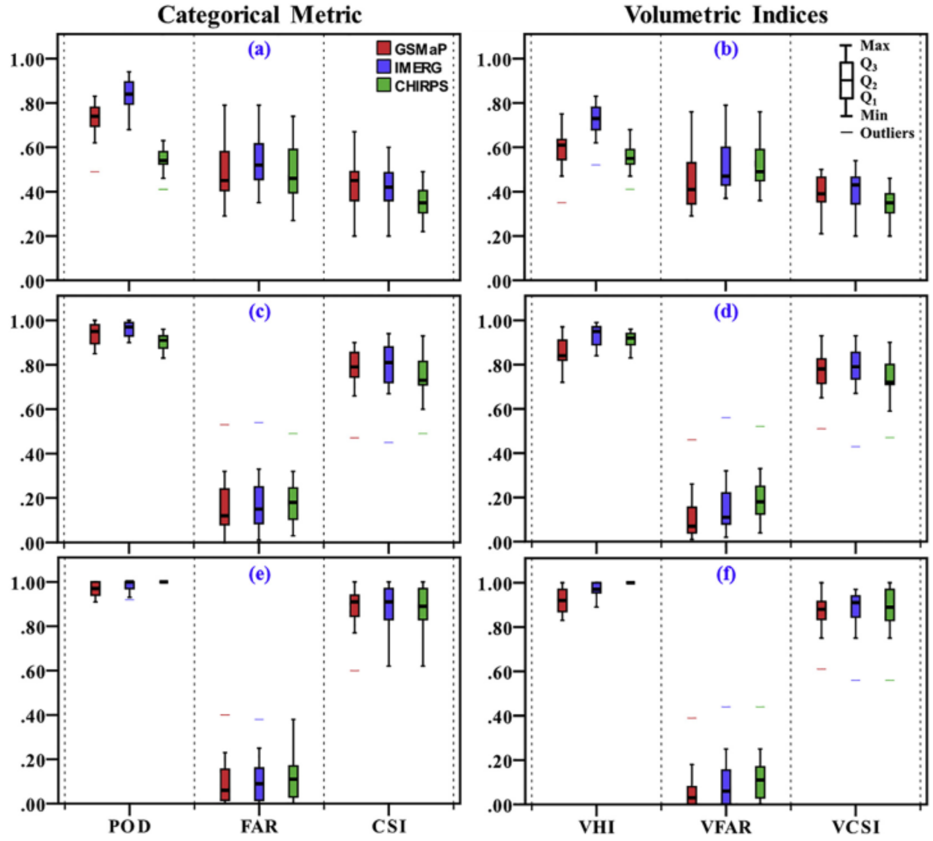

Fig. 3. Boxplot of categorical and volumetric index assessment of GSMaP, IMERG, and CHIRPS products at different temporal scales: daily (a, b), penta-day (c, d), and monthly (e, f). The bottom and top areas of the boxplot represent the first and third quartiles, the line beside the box represents the second quartile (median), the two lines at the bottom and top of the whisker represent the minimum and maximum values, and any line not between the whiskers denotes an outlier.

summary of the overall monthly assessment results. Fig. 2g–i show scatter plots of rain gauge observations and satellite estimates, and Fig. 3e and f depict boxplots of categorical and volumetric indices on a monthly temporal scale. The monthly assessment, shown in Table 2, indicates that CHIRPS exhibited higher performance in most statistical assessment measures (ME, POD, CSI, VHI, and VCSI). However, GSMaP has advantage in VFAR, along with IMERG in both r and RMSE. The result suggests that CHIRPS still had a lower correlation coefficient and higher FAR and VFAR. Among the three SPPEs, IMERG had the highest correlation coefficient ($r = 0.72$) and lowest RMSE (136.60 mm/month), whereas GSMaP had the largest RMSE (145.81 mm/month) and underestimated the monthly gauge-observed rainfall by a bias of 17% and ME of −49.33 mm. By contrast, CHIRPS and IMERG overestimated the monthly rain gauge–observed rainfall by a bias of 17% and 24%, respectively.

In Table 2, it is evident the CHIRPS performance on the monthly scale is promising and superior in its performance on the daily temporal scale; a similar result has been reported by previous studies (Zambrano-Bigiarini et al., 2017; Ayehu et al., 2018). The results have shown the value of POD ranging from 0.79 to 1.00, correlation coefficient ($r = 0.80$ to 0.88), value of FAR reach from 0.14 to 0.31, and value of CSI vary from 0.68 to 0.86. The good performance of CHIRPS perhaps due to the use CHP-Clim (Climate Hazard Precipitation Climatology), calibration with TPMA 3B42, and addition of rain gauge station data in the CHIRPS datasets algorithm (Funk et al., 2015). The other two SPPEs were more consistent with rain gauge observations on the monthly temporal scale than on the daily and penta-day scales.

4.1.4. Seasonal assessment

Bali Island has two distinct wet and dry seasons. Therefore, in this study, we characterized two seasons to investigate how the precipitation estimations are influenced by the monsoon. The wet season runs from November to April and is influenced by the northwest monsoon, and the dry season runs from May until October and is influenced by the southeast monsoon (Aldrian et al., 2003; As-syakur et al., 2011). The monthly rainfall data for each rain gauge and GSMaP, IMERG, and CHIRPS products were stratified by seasonal rainfall (wet and dry season). The seasonal rainfall assessments of the three satellite products and rain gauge observation are shown in Fig. 2j–l (wet season), Fig. 2m–o (dry season), and Table 2. The positive bias and ME values indicated that both the IMERG and CHIRPS overestimated rainfall observed by the rain gauge during the wet and dry seasons, whereas a negative bias and ME for GSMaP in all seasons indicated that it underestimated rainfall, as observed by rain gauges. The RMSE values showed that the IMERG had a relatively small error in measuring rainfall from the rain gauges during the wet and dry seasons, with values of 514.16 and 396.46 mm/6 months, respectively, compared with a high RMSE score registered for both GSMaP and CHIRPS during the same seasons. Moreover, the IMERG more accurately represented the rainfall from rain gauge observations for all seasons, with values of $r = 0.75$ (wet season) and $r = 0.81$ (dry season). All satellite products had the ability to detect rainfall accurately in all seasons, as determined

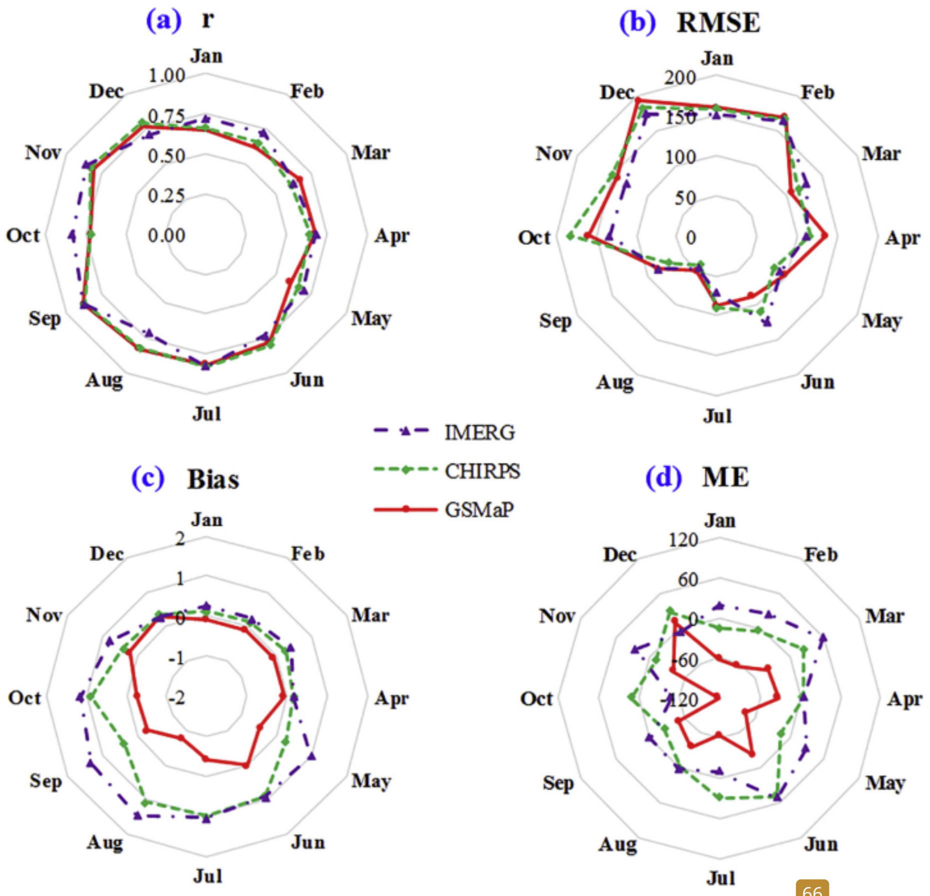

Fig. 4. Continuous statistical assessment of GSMaP, IMERG, and CHIRPS for each month: **(a)** correlation coefficient (r), **(b)** root mean square error (RMSE), **(c)** relative bias (bias), and **(d)** mean error (ME). The RMSE and ME value are presented in mm/month.

on the basis of the perfect values of POD (1.00), FAR (0.01), CSI (0.99), VHI (1.00), VFAR (0.01), and VCSI (0.99).

The performance of SPPEs was also assessed for each month in Bali Island. The performance statistics were calculated using the monthly average of each month (Fig. 4). As seen from the results of the continuous statistical analysis presented in Fig. 4a, the correlation coefficient for all three SPPEs was generally high (0.61–0.88) during all months. The correlation coefficient for IMERG was relatively higher compared with that for GSMaP and CHIRPS, except in the months of March, June, August, and December. In the month of March, the highest correlation coefficients were recorded for GSMaP. In June and December, CHIRPS had the highest correlation value. IMERG had the lowest RMSE in most months of the wet season (November–April), except in March, whereas CHIRPS had the lowest RMSE in the months of May, August, and September (dry season). Based on the performance of CHIRPS during the months of the dry season, Toté et al. (2015) suggested its use in drought monitoring and estimation. Fig. 4c and d reveal that IMERG and CHIRPS overestimated rain gauge–observed rainfall every month, whereas GSMaP overestimated rainfall only in November and December, as evident in the positive values of bias and ME.

Fig. 5 presents the categorical and volumetric assessments for each month. The performance of all three SPPEs was fair during the wet months and was in good agreement with rain gauge observations, as evidenced by the high POD, CSI, VHI, and VCSI values and low FAR and VFAR values. This is probably because the number of hit values was clearly larger than the number of false and missed events throughout the wet months. CHIRPS had higher values of POD, VHI, CSI, and VCSI compared with GSMaP and IMERG for each month; this result was consistent with those of Toté et al. (2015) and Paredes Trejo et al. (2016). GSMaP had the lowest value of FAR and VFAR for each month, whereas CHIRPS still had the highest value of FAR and VFAR during June–October. The highest value of FAR (0.4) and VFAR (0.31) was found in another study in Moçambique (Toté et al., 2015). The low FAR and VFAR values in CHIRPS were because of the overestimation of precipitation events, which may be associated with its calibration with TMPA 3B42 (Ayehu et al., 2018).

4.2. Performance assessment: different elevations

Terrain effect might be a crucial factor that influences the effectiveness of SPPEs (Dinku et al., 2010). The evaluation at different elevations select the daily rainfall data scale because the daily rainfall data is the most input to water balance and hydrological models (Rahmawati and Lubczynski, 2018). The elevation range of the selected rain gauge stations in this study was from 12 to 1173 m above sea level (m.a.s.l.). Table 3 shows the evaluation statistics for GSMaP, IMERG, and CHIRPS data on the daily rainfall scale at different altitude ranges. Values of POD, CSI, VHI, VCSI, and the coefficient correlation of CHIRPS were lower than those of GSMaP and IMERG at all elevations. IMERG

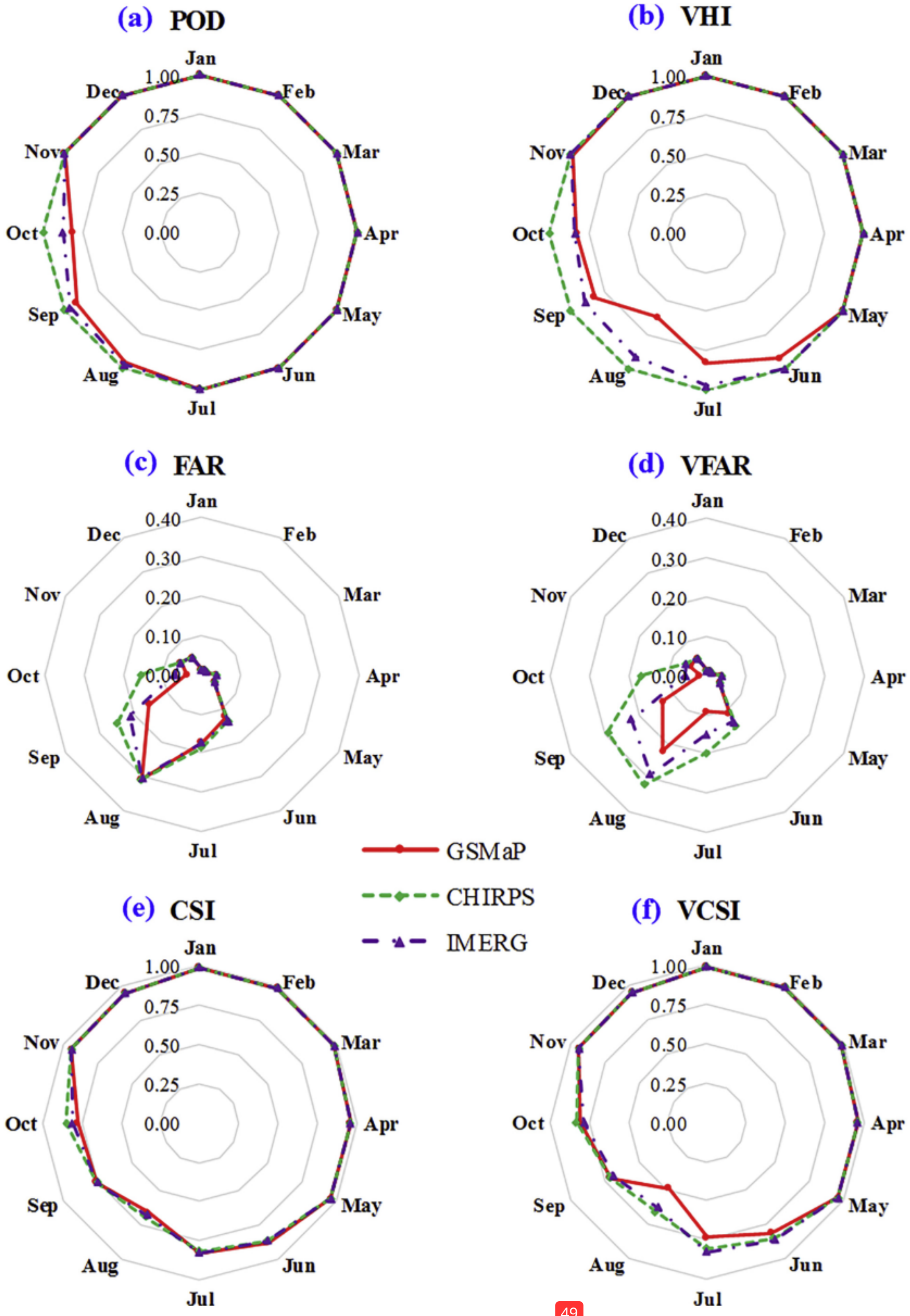

Fig. 5. Categorical and volumetric assessment of GSMaP, IMERG, and CHIRPS for each month: **(a)** probability of detection (POD), **(b)** volumetric hit index (VHI), **(c)** false alarm ratio (FAR), **(d)** volumetric false alarm ratio (VFAR), **(e)** critical success index (CSI), and **(f)** volumetric critical success index (VCSI).

Table 3

Performance assessment of GSMaP, IMERG, and CHIRPS at the daily rainfall scale at different elevations.

Elevation (m)	SPPEs	r	Bias	RMSE	ME	POD	FAR	CSI	VHI	VFAR	VCSI
< 400	GSMaP	0.28	−0.20	18.28	−2.00	0.74	0.51	0.42	0.60	0.46	0.39
	IMERG	0.32	0.16	18.07	−0.33	0.83	0.55	0.40	0.72	0.51	0.40
	CHIRPS	0.23	0.10	18.56	−0.14	0.55	0.51	0.34	0.56	0.53	0.34
400–800	GSMaP	0.25	−0.17	14.99	−1.01	0.71	0.47	0.43	0.54	0.43	0.38
	IMERG	0.29	0.28	15.11	1.36	0.84	0.50	0.45	0.71	0.48	0.42
	CHIRPS	0.23	0.31	15.53	1.50	0.50	0.45	0.36	0.52	0.49	0.35
800–1200	GSMaP	0.39	0.14	15.16	0.16	0.75	0.42	0.48	0.65	0.37	0.46
	IMERG	0.35	0.86	15.12	2.93	0.90	0.54	0.44	0.80	0.53	0.42
	CHIRPS	0.27	0.46	14.21	1.58	0.54	0.39	0.40	0.57	0.46	0.38

RMSE and ME are presented in mm/day.

exhibited a greater ability because it had the highest values of POD, CSI, VHI, VCSI, and r. The relatively good performance of IMERG at different altitudes can be attributed to the inclusion of the ancillary product for the development of the IMERG algorithm (Huffman et al., 2018). These results render IMERG a relatively better satellite precipitation product that might be used in regions with mixed terrain, such as Bali Island, to detect the patterns and variability of rainfall.

The performance of satellite products on the daily scale at different elevations is also presented in Figs. 6 and 7. Fig. 6 depicts the continuous statistical assessment of the SPPEs at different altitudes from 2015 to 2017. The SPPEs had correlation coefficients ranging from 0.05 to 0.65 irrespective of the variation in altitude (Fig. 6a and Table 4). The highest correlation (*r* = 0.65) was obtained for IMERG at the Ungasan rain gauge station at an elevation of 148 m.a.s.l. The lowest correlation (*r* = 0.05) was obtained for CHIRPS at the Telengan rain gauge station at an altitude of 96 m.a.s.l. GSMaP and CHIRPS products had a substantially positive correlation with elevation, whereas IMERG yielded constant values with increasing altitude. On the basis of the bias and ME values, both IMERG and CHIRPS overestimated rainfall at most altitudes, whereas GSMaP underestimated rainfall at low and middle altitudes but slightly more accurately estimated rainfall at high altitudes (Fig. 6b and d). Furthermore, the RMSEs of all SPPEs had a negative relationship with elevation (Fig. 6c). CHIRPS had the lowest average RMSE (14.21 mm/day) at high elevations compared with GSMaP and IMERG (15.16 and 15.12 mm/day, respectively). The performance of the SPPEs was relatively good at high elevations because of the inclusion of the elevation indicator (Funk et al., 2015) in the development of datasets; moreover, the use of microwave sensors to estimate rainfall is more accurate in open areas than in complex areas (Kenawy et al., 2015).

Scatterplots of the assessment of categorical and volumetric indices for each rain gauge at various elevations are shown in Fig. 7. All statistical indices show a similar trend for GSMaP, IMERG, and CHIRPS products. The slopes of the trend lines for POD and VHI for IMERG are higher than those for both GSMaP and CHIRPS, indicating a large improvement in the probability of the IMERG product correctly estimating rainfall over complex terrains (Fig. 7a and b). Consistent with the result of the performance of IMERG at high altitudes, Xu et al. (2017) also found that the GPM IMERG was superior at different elevations. However, the competencies of GSMaP and CHIRPS products in detecting rainfall events decreased with altitude. An analysis of the relationship between satellite ability (i.e., FAR, VFAR, CSI, and VCSI) and altitude showed that the FAR and VFAR of all SPPEs had a negative association with elevation; furthermore, the CSI and VCSI had a positive association with elevation, indicating an improvement in the SPPEs with respect to the probability of accurately detecting rainfall over high altitudes. This

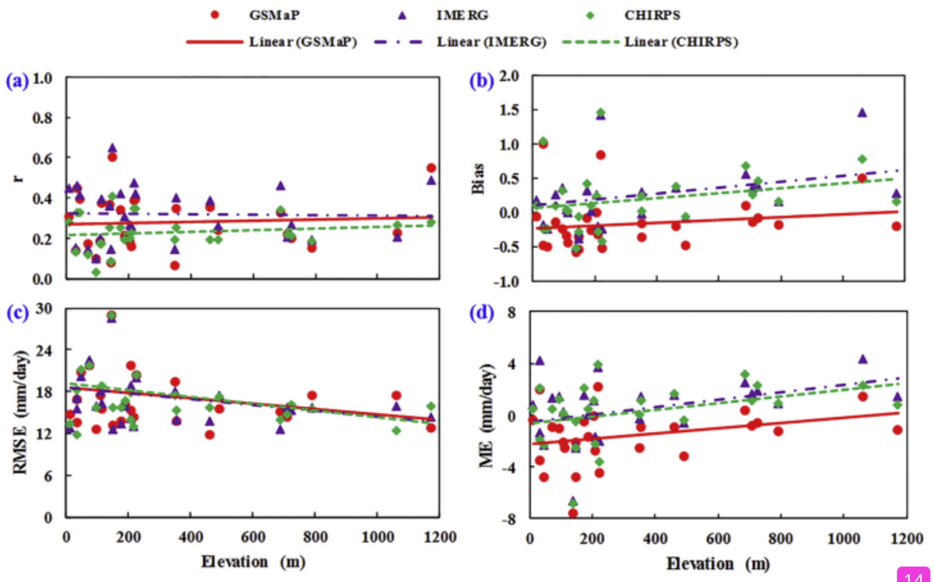

Fig. 6. Relations between continuous statistical assessment and elevation for GSMaP, IMERG, and CHIRPS: **(a)** correlation coefficient (r), **(b)** relative bias (bias), **(c)** root mean square error (RMSE), and **(d)** mean error (ME). The red line, purple dashed-dotted line, and green dashed line show the estimated linear trends. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

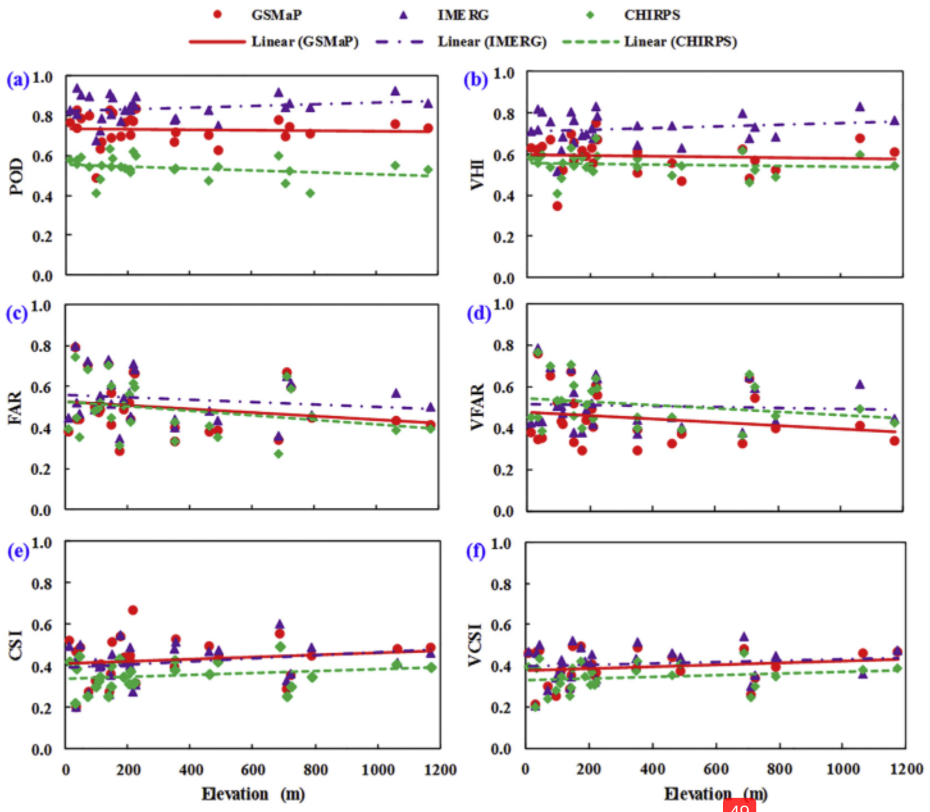

Fig. 7. Relations between categorical and volumetric assessment and elevation for GSMaP, IMERG, and CHIRPS: **(a)** probability of detection (POD), **(b)** volumetric hit index (VHI), **(c)** false alarm ratio (FAR), **(d)** volumetric false alarm ratio (VFAR), **(e)** critical success index (CSI), and **(f)** volumetric critical success index (VCSI).

Table 4
Correlation coefficients for GSMaP, IMERG, and CHIRPS at each rain gauge station.

Station name	Latitude	Longitude	Elevation (m.a.s.l)	GSMaP	IMERG	CHIRPS
Poh Santen	−8.37	114.67	12	0.30	0.45	0.28
Singaraja	−8.11	115.08	32	0.14	0.15	0.13
Buagan	−8.68	115.20	35	0.45	0.46	0.33
Pedawa	−8.24	115.03	47	0.39	0.41	0.33
Umadesa	−8.22	114.93	72	0.17	0.14	0.12
Telengen	−8.52	115.48	96	0.10	0.10	0.05
Sading	−8.60	115.19	109	0.19	0.20	0.17
Klungkung	−8.53	115.41	113	0.37	0.40	0.17
Pulukan	−8.40	114.84	139	0.36	0.36	0.25
Mambal	−8.55	115.22	146	0.08	0.15	0.08
Unggasan	−8.83	115.17	148	0.60	0.65	0.41
Gadungan	−8.48	115.09	174	0.34	0.42	0.25
Benel	−8.28	114.60	189	0.21	0.30	0.20
Dauhwaru	−8.32	114.65	205	0.18	0.26	0.20
Tibutanggang	−8.38	114.73	209	0.16	0.26	0.23
Grokgak	−8.21	114.78	217	0.39	0.48	0.35
Sawan	−8.15	115.19	223	0.39	0.42	0.35
Penatahan	−8.72	115.52	351	0.06	0.15	0.19
Tegallalang	−8.44	115.13	353	0.35	0.40	0.25
Pidpid	−8.46	115.28	461	0.35	0.39	0.20
Rendang	−8.38	115.58	490	0.24	0.26	0.19
Bongancina	−8.42	115.43	687	0.33	0.46	0.34
Gitgit	−8.34	115.04	710	0.22	0.20	0.22
Munduk	−8.20	115.14	724	0.20	0.26	0.22
Pempatan	−8.26	115.05	791	0.15	0.20	0.19
Kedisan	−8.36	115.03	1062	0.22	0.21	0.27
Pengotan	−8.28	115.38	1173	0.55	0.49	0.28

result also revealed the possibility of increasing the accuracy of satellite rain retrieval over regions with diverse terrain.

4.3. Performance assessment: various rainfall intensities

The PDF, which presents useful information on the histogram frequency of a dataset, has been used in many studies to evaluate the performance of SPPEs (Chen et al., 2013; Tang et al., 2016; Ma et al., 2018). Therefore, PDF was used in the present study to evaluate the performance of GSMaP, IMERG, and CHIRPS in detecting the frequency of rainfall events at different rainfall intensities. Fig. 8 shows the PDF of the study region, wherein the PDFs of daily rainfall events at different intensities and elevations were calculated from January 2015 to December 2017.

Compared with rain gauges, all three SPPEs tended to underestimate the frequency of light (0–1 mm/day) and heavy rainfall events (> 50 mm/day) but overestimate the frequency of moderate rainfall events (5–10 mm/day; Fig. 8a). Underestimation by GSMaP products might be due to the currently used GSMaP_MVK algorithm that estimates rainfall only by using the microwave radiometer algorithm, which presents the possibility of removing some informative signals from the light rainfall events (Ushio et al., 2009). Furthermore, IMERG and CHIRPS tended to overestimate the frequency of moderate rainfall events (10–50 mm/day), whereas GSMaP tended to underestimate the same. Moreover, GSMaP and IMERG products overestimated the frequency of light rainfall events (1–5 mm/day), whereas CHIRPS tended to underestimate it. This result is in general agreement with those of other studies, one of which demonstrated that CHIRPS overestimated the frequency of rainfall events between 0 and 20 mm (Toté et al.,

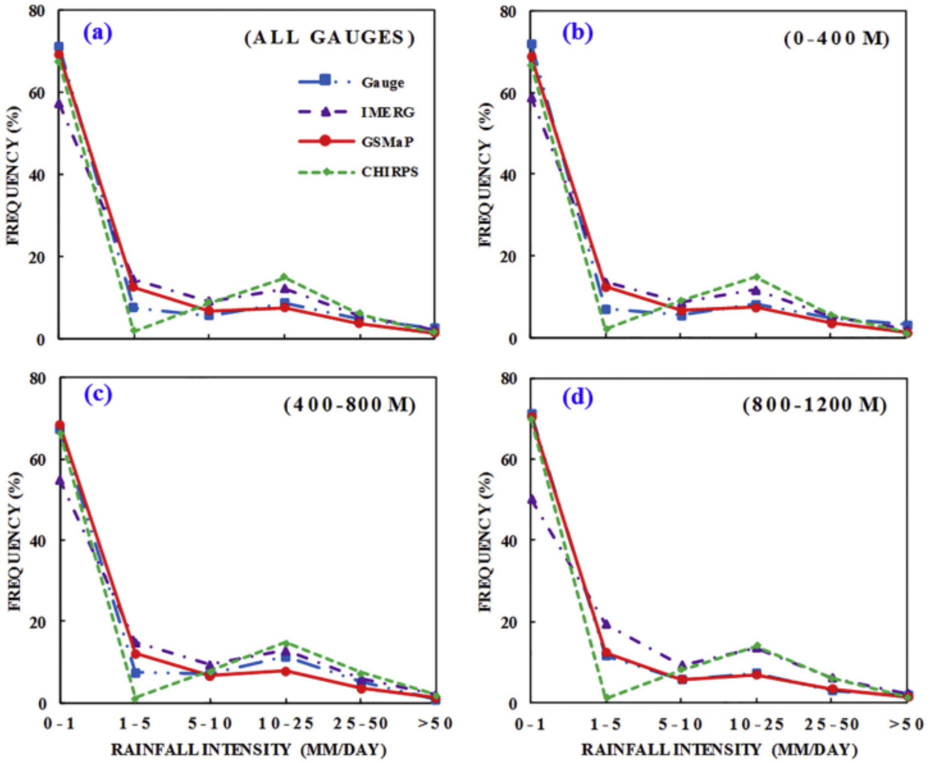

Fig. 8. Probability distribution functions (PDF) of rainfall occurrence observed by rain gauges and rainfall estimates from GSMaP, IMERG, and CHIRPS over different elevations.

2015), and another demonstrated that GSMaP underestimated the frequency of moderate-intensity rainfall (Deng et al., 2018).

With respect to rainfall intensity at different altitudes (Fig. 8b–8d), the three SPPEs exhibited distribution patterns for the frequency of rainfall events, which were similar to those of rain gauges for moderate rain events (10–50 mm/day) at low and middle altitudes. Products based on IMERG and GSMaP overestimated light rainfall (1–5 mm/day); however, CHIRPS products underestimated light rainfall compared with gauge-based observation. For the highest daily rainfall rates (> 50 mm), the estimation by all satellite products was closer to measurements by rain gauges at middle and high altitudes but below the measurements by rain gauges at low altitudes. Of the three SPPEs, GSMaP agreed well with rain gauge observations at high altitudes in terms of the frequency of rainfall events of all intensities (Fig. 8d). GSMaP exhibited relatively good performance in detecting the frequency of rainfall events with different intensities.

5. Conclusion

To determine the quality of their performance, estimates of GSMaP, IMERG, and CHIRPS products were compared with rain gauge observations over Bali Island from January 2015 to December 2017 with respect to different temporal scales (daily, penta-day, monthly, and seasonal), terrain factors, and rainfall intensities by using a high-density rain gauge network. Comparison a point to grid–based according Fig. 1 was implemented to evaluate the SPPEs using continuous, categorical, and volumetric statistical indices. The main conclusions are summarized as follows:

1. IMERG products performed better on daily, penta-day, and seasonal time scales, whereas CHIRPS outperformed the others at the monthly scale. GSMaP products had a negative bias for all considered time scales (daily, penta-day, monthly, and seasonal).
2. IMERG demonstrated higher ability to detect rainfall events at different altitudes but overestimated the rainfall events at high altitudes. GSMaP underestimated rainfall events at low altitudes, whereas IMERG and CHIRPS overestimated rainfall events with respect to rain gauge observations.
3. Comparing their ability to detect rainfall events of various intensities, GSMaP, IMERG, and CHIRPS tended to underestimate the frequency of light rainfall events (0–1 mm/day) and heavy rainfall events (> 50 mm/day) but overestimated the frequency of moderate rainfall events (5–10 mm/day). IMERG and CHIRPS overestimated the frequency of moderate rainfall events (10–50 mm/day), whereas GSMaP underestimated it. GSMaP estimations agreed well with rain gauge observations in terms of the frequency of rainfall of all intensities at high altitudes.

Because the capability of the SPPEs was unsatisfactory, detecting and estimating accurate rainfall in regions with diverse terrains such as Bali Island is challenging. The accessibility of high temporal and spatial resolution rainfall data is essential for retrieval of data on a small island. The scope of the current study was limited to evaluating the performance of different SPPEs on the hourly time scale. A high temporal resolution analysis and improved SPPEs from the use of cloud-top microphysical properties along with high spatiotemporal resolution of atmospheric thermodynamic state (e.g., Liu et al., 2016a; Liu et al., 2016b; Liu et al., 2020) would be beneficial for assessing extreme weather phenomena, such as heavy precipitation events and tropical cyclones, as well as flood monitoring.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

We thank the data providers of GSMaP, IMERG, and CHIRPS. We also acknowledge the Balai Wilayah Sungai Bali-Penida Ministry of Public Works and Human Settlements of Indonesia for its support in obtaining gauge station rainfall data over Bali Island. C.Y.L, P.A., and G.R.L were supported by the Ministry of Science and Technology of Taiwan under grant numbers: MOST 106-2111-M-008-001-MY2 and MOST 108-2625-M-008-015. W.R.H. was supported by MOST 106-2628-M-003-001-MY4 and MOST 108-2625-M-003-004. P.A. was supported in part by Academic Sinica (grant number: AS-TP-107-M10-3) and the International Ph.D Program in Environmental Science and Technology (University System of Taiwan) at National Central University, Taiwan.

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