Assessment of Satellite Precipitation Data Sets for High Variability and Rapid Evolution of Typhoon Precipitation Events in the Philippines

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Assessment of Satellite Precipitation Data Sets for High Variability and Rapid Evolution of Typhoon Precipitation Events in the Philippines

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Key Points:

- Satellite precipitation data sets (SPDs) were evaluated during typhoon-related heavy precipitation events in the Philippines for the first time
- The high spatial resolution SPDs (0.04° and 0.1°) were assessed in this study
- The performance of SPDs varies clearly with terrain complexity

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Abstract Extreme weather events, such as typhoons, have occurred more frequently in the last few decades in the Philippines. The heavy precipitation caused by typhoons is difficult to measure with traditional instruments, such as rain gauges and ground-based radar because these instruments have an uneven distribution in remote areas. Satellite precipitation data sets (SPDs) provide integrated spatial coverage of rainfall measurements, even for remote areas. However, the speed and direction of the wind has the interaction with terrain, which leads the uncertainty of the SPDs. This study performed sub-daily assessments of near-real-time and high resolution SPDs (i.e., IMERG, GSMaP, and PERSIANN data sets) during five typhoon-related heavy precipitation events in the Philippines, with the analysis under the impact due to wind and terrain effect. The aforementioned assessments were performed through a point-to-grid comparison by using continuous and volumetric statistical validation indices for the 34-knot wind radii of the typhoons, rainfall intensity, terrain, and wind velocity effects. The results revealed that the IMERG exhibited good agreement with rain gauge measurements and exhibited high performance in detecting rainfall. The GSMaP data set overestimated the gauge observations during peak rainfall, while the IMERG and PERSIANN data sets considerably underestimated rainfall. The GSMaP exhibited the best performance for detecting heavy rainfall at high elevations, whereas IMERG exhibited the best performance for rainfall detection at low elevations. The IMERG exhibited a strong ability to detect heavy rainfall under various wind speeds.

1. Introduction

Heavy precipitation refers to a rainfall event that occurs in according to certain area; exceeds a certain threshold; tends to be of short duration; can threaten human activity; and often causes natural disasters (such as floods and landslides) that result in social problems, environmental damage, and material losses (Bell et al., 2004; Chen & Wu, 2016; Hong et al., 2006; Stampoulis et al., 2013; H. Wu et al., 2012). Heavy precipitation can be triggered by events such as tropical cyclones (typhoons) (D. Wang et al., 2016). Typhoons can cause heavy precipitation from inside the eye to the eyewall of the storm, a distance that can tend to hundreds of kilometers across (Kimball, 2008; Lonfat et al., 2007; Y. Wang et al., 2009; Yokoyama & Takayabu, 2008). Typhoons can also cause heavy rainfall in distant regions located thousands of kilometers from the center of a typhoon (Chen & Wu, 2016; Ross & Kurihara, 1995; Y. Wang et al., 2009). The quantity of rainfall caused by typhoons is affected by several factors, such as the internal typhoon structure, track variations, large-scale moisture convergence, convection strength, cloud microphysics, typhoon interaction at midlatitude, and typhoon interaction with the topography (Chen & Wu, 2016; Cheung et al., 2018; Hon, 2020; Huang & Lin, 2014; Jones et al., 2003; C. C. Wu et al., 2009; Yang et al., 2011; Yu & Cheng, 2013; Zhang et al., 2010). Monitoring the heavy rainfall caused by typhoons with conventional instruments (e.g., rain gauges) is difficult because their diameters range from 100 to 2,000 km (C. Huang et al., 2019). Therefore, achieving an accurate quantitative estimation of heavy rainfall caused by typhoon events represents the largest challenge in hydrometeorological research and natural disaster modeling.

The analysis of heavy precipitation requires an accurate precipitation data set with global coverage as well as high spatial and temporal resolutions (J. Liu et al., 2019; C.-Y. Liu et al., 2020; Setiawati et al., 2016). Accurate rainfall data with high spatial and temporal resolution at regional and global scales are difficult to access in the fields of hydrology and weather forecasting. In situ measurements from rain gauge stations can supply reliable point-scale rainfall data (Duan et al., 2016). However, rain gauge stations are unevenly distributed, with few such stations being found in remote and mountainous areas, which limits the quantity of accurate spatial and temporal data that can be obtained for these areas (Javanmard et al., 2010; Ji et al., 2020). Weather radar can provide local precipitation data with sufficiently high spatial and temporal resolution. However, these data are affected by deviations from electromagnetic signals due to the effect of the terrain in mountainous areas (Z. Li et al., 2013).

The rapid development of remote sensing techniques in the fields of hydrology and meteorology has resulted in the development of several satellite-based precipitation estimation methods with global coverage as well as high spatial and temporal resolution (Nashwan et al., 2020; Y. Wu et al., 2019). Satellite precipitation data sets (SPDs) released online to the public can overcome the problem caused by the unavailability of rain gauge stations and weather radar data. Rainfall estimation techniques using SPDs are broadly based on the thermal infrared (TIR) radiation of geostationary satellites, the passive microwave (PMW) radiations recorded by sensors in low Earth-orbiting satellites, or a combination of TIR and PMW radiations (Duan et al., 2016; Levizzani & Cattani, 2019; J. Liu et al., 2019). These estimation techniques are not perfect in terms of accurately predicting rainfall intensity (Freitas et al., 2020). Therefore, calibration and validation are necessary before SPDs can be used for hydrological modeling or meteorological disaster observation. Global coverage can be achieved by several SPDs, such as the Precipitation Estimation from Remotely Sensed Information Using Artificial Neural Networks (PERSIANN; Hsu et al., 1997), the Climate Prediction Center Merged Analysis of Precipitation (Xie & Arkin, 1997), the Climate Prediction Center Morphing Algorithm (CMORPH; Joyce et al., 2004), the Global Satellite Mapping of Precipitation (GSMaP; Okamoto et al., 2005), the Integrated Multi-satellitE Retrievals for Global Precipitation Measurement (IMERG; Hou et al., 2014), the Climate Hazards Group InfraRed Precipitation with Station (CHIRPS; Funk et al., 2015), and the Multisource Weighted-Ensemble Precipitation (Beck et al., 2017) data sets.

Revisions in the algorithms of SPDs have been made based on key studies which improved the capability of SPDs in detecting heavy rainfall. Studies have evaluated the performance of the SPDs during an extreme rainfall event, such as Tropical Rainfall Measuring Mission (TRMM), CMORPH, GSMaP, IMERG, and PERSIANN in the term of estimating daily rainfall (X. Huang et al., 2018; Palharini et al., 2020; Parida et al., 2017; Pombo & de Oliveira, 2015; Rashid et al., 2018; Tashima et al., 2020), peak rainfall intensity (Parida et al., 2017), weekly rainfall (Tashima et al., 2020), monthly rainfall (X. Huang et al., 2018; J. Liu et al., 2019), seasonal rainfall (W.-R. Huang et al., 2021), and annual rainfall (Huang et al., 2018; Liu et al., 2019); Palharini et al., 2020). The outcomes of these studies demonstrate the performance of SPDs in detecting heavy rainfall varies with the temporal variability of rainfall. Furthermore, since heavy rainfall often occurs in the short time period (sub-daily) that is scarcely determined by daily rainfall observation from rain gauge stations (Ramadhan et al., 2022), therefore, the ability of SPDs to measure heavy participation on a sub-daily scale must be investigated.

The complex topography and mountainous regions with orographic convection and low-troposphere winds represent a challenge in rainfall estimation by satellites (Shige et al., 2013). Evaluation studies of SPDs on complex topography are still required to further advance the product algorithms (Bartsotas et al., 2018; Derin & Yilmaz, 2014; Lu & Yong, 2018; Thakur et al., 2019; Wang & Yong, 2020). Various studies that have compared the abilities of SPDs to detect heavy rainfall caused by landfalling typhoons have suggested performing a comparison in terms of rainfall distribution and spatiotemporal variability (S. Chen et al., 2013; C. Huang et al., 2019; Pham & Vu, 2020; Yu et al., 2009), analyzing rain gauges in areas within 400 km of the center of a typhoon (D. Wang et al., 2016), rainfall detection on typhoon and non-typhoon events (W.-R. Huang et al., 2021), and using descriptive and categorical statistics to perform an analysis (Chen et al., 2013; Yu et al., 2009). However, it is noteworthy that no previous evaluation of SPDs has analyzed the effects of terrain and wind velocity. Therefore, the effects of terrain and wind velocity on the ability of SPDs to detect heavy precipitation caused by typhoons should be investigated. Additionally, the variability distribution and magnitude of rainfall induced by typhoon is closely linked with the rapid evolution of typhoon in time and location. The limited interpretation of the variability typhoon precipitation events is due to the irregular and limited distribution of rain gauge stations (Bregy et al., 2020). Hence, the near-real-time and high temporal-spatial resolution of SPDs are necessary to be carried out in this study.

The Philippines is an archipelago with more than 7,100 islands of complex topography (Bagtasa, 2017; Ramos et al., 2016). Two of its islands, namely Luzon in the north and Mindanao in the south, have long chains of mountains, whereas the Visayas region, which is located in the center of the country, consists of small islands (Bagtasa, 2017; Ramos et al., 2016). The Philippines frequently experiences typhoons that form in the Northwestern Pacific Basin (Bagtasa, 2017; Weinkle et al., 2012). Every year, approximately 19 typhoons cross the border of the Philippines, and half of these typhoons make landfall (Bagtasa, 2017; Cinco et al., 2016). Few studies have been conducted in the Philippines (e.g., Jamandre & Narisma, 2013; Ramos et al., 2016) to evaluate the performance of SPDs. These studies evaluated the skills of TRMM, CMORPH (Jamandre & Narisma, 2013; Ramos et al., 2016), GSMaP, and PERSIANN (Ramos et al., 2016) precipitation data sets at various rainfall intensities, spatial and temporal scales. The results of these studies demonstrate that the performances of SPDs diverse on the amount of rainfall, geographical location, and temporal distribution of rainfall. Furthermore, to the best of our knowledge, no study has assessed the performance of SPDs during heavy precipitation events caused by typhoons in the Philippines. Several studies have conducted in China (C. Huang et al., 2019; D. Li et al., 2022; D. Wang et al., 2016; Yu et al., 2009), Taiwan (S. Chen et al., 2013; W.-R. Huang et al., 2021), India (Reddy et al., 2022), Vietnam (Pham & Vu, 2020), and Western North Pacific (Sutton et al., 2022) to assess the ability of SPDS during heavy precipitation events caused by typhoons. Therefore, this study evaluated the performance of near-real-time three SPDs (IMERG, GSMaP, and PERSIANN), during five typhoons related heavy precipitation events in the Philippines between 2016 and 2018. The near-real time SPDs with a few hour of time latency are essential for hydrological prognosticating, monitoring and managing of disaster events due to extreme precipitation (Nguyen et al., 2020; Tang et al., 2017). The current study evaluated the performance of the aforementioned SPDs by comparing their data with those of ground rain gauges in terms of the 34-knot wind radius (R34) of a typhoon, rainfall intensity, and the effects of terrain and wind velocity. Section 2 describes the study area. Section 3 provides a detailed description of the data set and methodology used in this study. Section 4 describes the performance of the three SPDs in terms of rainfall intensity, terrain, and wind velocity effects. Finally, Section 5 summarizes our findings.

2. Study Area

The study area was the Philippines, which is located between 4°40′N and 21°10′N and between 116°40′E and 126°34′E. This country has a total area of 300,055 km^2 (Figure 1a). The Philippines is located off the southeast coast of continental Asia across the South China Sea in the strategic zone between China, Taiwan, Borneo, and Indonesia. The Philippines is surrounded by the sea and is the only Southeast Asian country to not border neighboring countries (Bautista, 2011). This country has a tropical maritime climate, and its seasonal changes are influenced by northeast and southwest monsoon activity (Cinco et al., 2016). The Philippines experiences a cool dry season from December to February, a hot dry season from March to May, and a rainy season from June to November (The Philippine Atmospheric, Geophysical and Astronomical Services Administration [PAGASA]). Precipitation is the essential factor that affects the weather and climate in the Philippines. The distribution of precipitation in the country differs from one region to another and depends on the direction of moisture-bearing winds and the location of mountain systems (PAGASA, n.d.). The mean annual precipitation of the Philippines ranges between 965 and 4,064 mm per year (PAGASA, n.d.). Precipitation in many areas of the Philippines is also influenced by typhoons (Ramos et al., 2016). Particular areas in the northern Philippines can receive approximately 50%–60% of their annual precipitation from passing typhoons (Kubota & Wang, 2009).

3. Data Sets and Methods

3.1. Data Sets

The multisource data sets used in this study can be categorized into four types: typhoon event data; traditional observational rainfall data obtained from surface rain gauges; precipitation information estimated from satellite measurements; and wind vector data, which constitute a reanalysis data set. The following subsections provide a brief description of these four types of data.

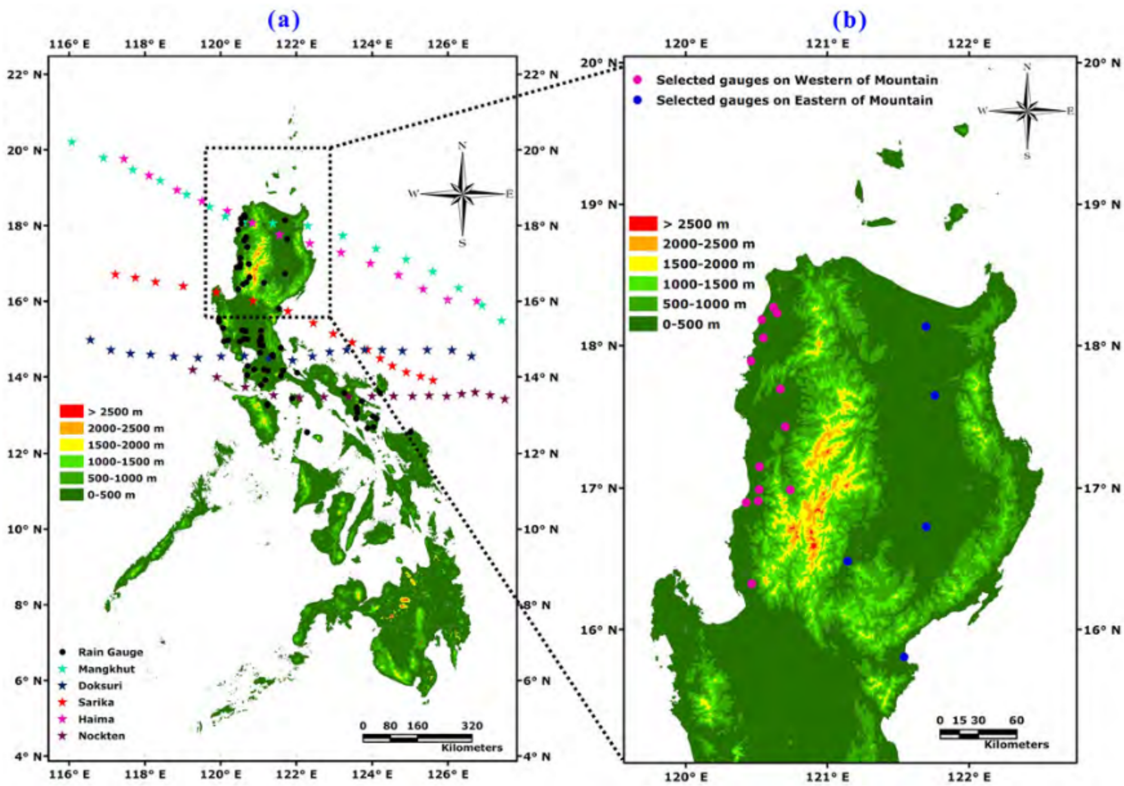

Figure 1. (a) Map of the Philippines, including distribution of the rain gauge stations (black dots), terrain, and tracks of the five typhoons (colored stars). (b) Map of Luzon island, including the selected rain gauge stations (colored dots) and terrain.

3.1.1. Typhoon Events

Table 1 presents brief descriptions of five typhoon events that passed over the Philippines. The information regarding the typhoons was provided by the International Best Track Archive for Climate Stewardship (IBTrACS). IBTrACS maintains an archive of the typhoon best track data for specific locations to add to the knowledge on the distribution, frequency, and intensity of typhoons worldwide. The World Meteorological Organization Tropical Cyclone Program has endorsed IBTrACS as an official recording and distribution resource for typhoon best track data (Knapp et al., 2010). The typhoon best track data contain 3-hr and long-term typhoon positioning records (from 1980 to the present). The typhoon track data are available online at https://climatedataguide.ucar.edu/

Table 1
Information Regarding Five Typhoon Events in the Philippines

Name of typhoon	Start time (UTC)	End time (UTC)	Duration (h)	Maximum wind speed (knots)	Number of stations	Maximum actual rainfall rate (mm/3 hr)	Maximum cumulative actual rainfall (mm)
Sarika	2016-10-14 15:00	2016-10-16 12:00	45	95	31	167.0	629.5
Haima	2016-10-18 21:00	2016-10-20 12:00	39	115	15	247.0	836.5
Nock-ten	2016-12-24 12:00	2016-12-26 9:00	45	105	16	183.0	284.0
Doksuri	2017-09-11 6:00	2017-09-12 15:00	33	40	21	151.5	436.0
Mangkhut	2018-09-13 18:00	2018-09-15 21:00	51	148	40	93.5	344.0

Table 2
Information Regarding Satellite Precipitation Data Sets Assessed in This Study

Data sets	Description	Spatial resolution (°)	Temporal resolution (hour)	Coverage area	Temporal extent	Provider
IMERG-E V06 B	Early run version 06 B (4 hr latency)	0.1	0.5	60°N–60°S	June 2000-present	NASA
GSMaP_NRT V7	Near real-time version 7 (4 hr latency)	0.1	1	60°N–60°S	2014-present	JAXA
PDIR-Now	Near real-time (15–60 min latency)	0.04	1	60°N–60°S	2000-present	CHRS-UCI

climate-data/ibtracs-tropical-cyclone-best-track-data. The five typhoons analyzed in this study passed over Luzon island. Typhoons Mangkhut and Haima passed through the north, Typhoon Sarika passed through the middle, and typhoons Nock-ten and Doksuri passed through the south of the Luzon island. The five typhoons were classified into various categories according to PAGASA's tropical cyclone intensity scale, namely typhoons (Mangkhut, Sarika, Haima, and Nock-ten), and tropical storms (Doksuri).

3.1.2. Data From Rain Gauge Measurements

The data from rain gauge measurements were used as a reference to evaluate the performance of the SPDs. Three-hour rainfall observation data for typhoons making landfall in the Philippines were obtained from PAGASA, the Department of Science and Technology, the Republic of the Philippines. A total of 66 rain gauge stations were selected based on whether the spatial distribution was affected by the R34 values of the typhoons and the completeness of the desired data. Table 1 lists the number of selected rain gauge stations within the R34 during the passing of the storm. PAGASA has made available high-quality rain gauge data for the five considered typhoon events.

3.1.3. IMERG Data Set

The high-resolution IMERG data set is an improvement on the TRMM Multisatellite Precipitation Analysis data set, whose global coverage data were made available from June 2000. The IMERG program was initiated by the National Aeronautics and Space Administration (NASA). Its algorithm intercalibrates, merges, and interpolates all available satellite microwave precipitation measurements, microwave-calibrated infrared measurements, surface rain gauge analyses, and other possible rainfall estimates on wide temporal and spatial scales for nearly the entire globe (Huffman, Bolvin, et al., 2019; Huffman, Stocker, et al., 2019). The IMERG data set provides half-hourly, daily, and monthly rainfall estimation at a spatial resolution of 0.1° with 60°N–60°S of global coverage. The IMERG data set contains three types of data in terms of time-release, namely early run, late-run, and final-run data. The time-release delay is 4 hr for the early run data, 12 hr for the late-run data, and 3.5 months for the final-run data (Huffman, Bolvin, et al., 2019; Huffman, Stocker, et al., 2019). This study used the early run Level-3 IMERG half-hourly data from version 06B (Table 2). The early run data set presents relatively fast result for instantaneous natural hazard monitoring and management by only applying the forward morphing method to derive PMW retrievals (Huffman et al., 2020).

3.1.4. GSMaP Data Set

The GSMaP data set is a satellite-based precipitation data set constructed by the Core Research for Evolutional Science and Technology program under the authority of the Japan Science and Technology Agency between 2002 and 2007, and the aforementioned program was extended by the JAXA (Japan Aerospace Exploration Agency). The GSMaP algorithm merges information from various PMW sensors of low Earth orbit satellites and infrared sensors on geostationary satellites to create a high-precision precipitation data set (Kubota et al., 2007; Ushio et al., 2009). The GSMaP data set is available in near-real-time, post-real-time, and reanalysis versions. The near-real-time versions consist of two data sets: the GSMaP near-real-time (GSMaP_NRT) and GSMaP Gauge near-real-time (GSMaP_Gauge_NRT) data sets. The post-real-time versions are the GSMaP Moving Vector with Kalman filter (GSMaP_MVK) and GSMaP_Gauge data sets. This study used the GSMaP_NRT version 7 data set (GSMaP_NRT V7), which has a temporal resolution of 1 hr, the spatial resolution of 0.1° × 0.1°, worldwide coverage (60°N–60°S), and contains data from 2014 to the present (Table 2). The time-release delay of the near-real-time GSMaP data set is 4 hours. The precipitation rate is acquired based on a cloud moving vector extracted from two successive infrared images and only forward propagation of Kalman filters (Kubota et al., 2020).

3.1.5. PERSIANN Data Set

The PERSIANN data set was established by the Center for Hydrometeorology and Remote Sensing (CHRS) at the University of California, Irvine (UCI), in association with NASA and the Global Network on Water and Development Information for Arid Lands of the United Nations Educational, Scientific and Cultural Organization. The PERSIANN retrieval algorithm is primarily based on integrated infrared imagery from geosynchronous satellites, with forecasts generated by an artificial neural network to transform infrared imagery into global rainfall data (Sorooshian et al., 2000). PERSIANN includes four precipitation data sets, namely the PERSIANN, the PERSIANN-Cloud Classification System (PERSIANN-CCS), the PERSIANN-Climate Data Record (PERSIANN-CDR), and PERSIANN Dynamic Infrared Rain Rate near-real-time (PDIR-Now) data sets. PERSIANN contains hourly rainfall estimates from March 2000 to the present with a spatial resolution of 0.25° and global coverage (60°N–60°S). PERSIANN-CCS contains hourly rainfall data from January 2003 to the present with worldwide coverage and a spatial resolution of 0.04°. PERSIANN-CDR contains daily global rainfall data from January 1983 to the present at a spatial resolution of 0.25°. PDIR-Now contains real-time global precipitation estimates from March 2000 to the present at a spatial resolution of 0.04°. All the PERSIANN data sets are accessible and have been widely used for various studies by researchers and professionals in the fields of climate, hydrology, water resource management, and disaster modeling. This study used the PDIR-Now precipitation data set with 15 min to 1-hr time-release delays (Table 2). The rainfall estimation retrieves depend on temperature, size, and texture characteristics of the cloud at temperatures under 273K. The short time delay of PDIR-Now is potential to use for observing and evaluating hydroclimate natural hazard disasters due to heavy precipitation (Nguyen et al., 2020).

3.1.6. Wind Data

The wind data used in this study was ERA5, which is a grid reanalysis data set obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF). ERA5 contains the latest ECMWF atmosphere, land surface, and ocean reanalysis data for global climate monitoring (Hersbach et al., 2020). Through reanalysis, model data containing observations from around the world can be integrated into a complete and worldwide consistent data set (Hersbach et al., 2020; Olauson, 2018; Ramon et al., 2019). ERA5 is frequently used in various applications and outperforms previous reanalysis methods (Dee et al., 2011; Hersbach et al., 2020). It provides long-term (1979 to present) hourly estimates of variables on pressure levels at a spatial resolution of 0.25°. This study used the variables u (eastward) and v (northward) of the wind vector components at a height of 10 m above the surface. The positive and negative u indicate the wind flows from west and east, respectively. The positive and negative v represent the wind comes from south and north. The wind speed value is obtained from the square root of the sum of the squares of the components u and v. The wind direction is indicated by the angle formed by the components u and v. Details calculation of wind speed and wind direction can be seen in Ostrenga (2019). The aforementioned data set provided by Copernicus Climate Change Service (C3S) and can be downloaded from https://cds.climate.copernicus.eu/cdsapp#!/data%20set/reanalysis-era5-land?tab=form.

3.2. Methods

A point-to-grid comparison was performed to compare the point-based rain gauge measurement data with the grid SPD and grid reanalysis wind data (Fenta et al., 2018; C.-Y. Liu et al., 2020). The performance of the SPDs was assessed in terms of the 3-hr temporal scale, rainfall intensity, the terrain, and wind velocity effect by comparing the precipitation estimates with the rain gauge measurements. The comparison between SPDs estimates and rain gauge measurements was carried out when the rain gauge is within R34 during the passing of the storm. The value of R34 indicates the typhoon size. The half-hourly IMERG estimation and hourly GSMaP and PERSIANN estimation data was aggregated to 3-hr rainfall data so that their temporal resolution matched that of the rain gauge measurements. The missing data from both the rain gauge station and the SPDs is only a small part of the data so it is omitted in the analytical process. The 3-hr rainfall estimates obtained by the SPDs were assessed as functions of rainfall intensity. The 3-hr rainfall intensities for all precipitation data sets were categorized into the following five groups: 0–5 mm/3 hr (light rain events), 5–15 mm/3 hr (moderate rain events), 15–25 mm/3 hr (heavy rain events), 25–50 mm/3 hr (very heavy rain events), and >50 mm/3 hr (extreme rain events) (Tan et al., 2015; J. Liu et al., 2015; Xu et al., 2017). The terrain zonation was done using contour map downloaded from http://203.177.51.124/gis-data. Using that contour, the Philippines was divided into six elevation classes, namely 0–500, 500–1,000, 1,000–1,500, 1,500–2,000, 2,000–2,500, and >2,500 m. The distribution of rain gauge stations based on elevation is mostly found at elevation intervals of 0–500 m, while at elevation intervals of 1,000–1,500 m, there are only eight rain gauge stations. Based on the rain gauge stations distribution on the elevation classes, the performance of the SPDs in terms of the terrain effect was evaluated into two elevation categories: ≤1,000 m (low altitude) and >1,000 m (high altitude). The evaluation of the SPD performance in terms of wind velocity was conducted by dividing wind speed into the following five categories: 0–3, 3–6, 6–9, 9–12, 12–15, and ≥15 m/s. The distribution of the SPD performance in terms of wind direction was modeled as a wind rose, in which wind direction was divided into eight categories: north (N), northeast (NE), east (E), southeast (SE), south (S), southwest (SW), west (W), and northwest (NW).

The performance of the SPDs was evaluated by conducting a quantitative analysis of two categories of validation statistics. The first statistical category was continuous statistics, which describe the differences between satellite rainfall magnitude and ground rainfall station measurements, which include bias ratio (BR), correlation coefficient (*R*), mean error (ME), and root mean square error (RMSE). BR refers to the tendency of SPDs to underestimate or overestimate rainfall compared with the rain gauge station measurements. The perfect score for BR is 1. A BR below 1 indicates that the satellite data sets tend to underestimate rainfall compared with the ground rainfall measurements, and a BR above 1 indicates that the satellite data sets tend to overestimate rainfall. The parameter *R* measures the strength of the linear association between the satellite rainfall estimates and the ground-based observations. A value of 1 is the ideal score for *R*. ME indicates the average error in rainfall measurements between the SPDs and the ground-based observations. RMSE reflects the average deviation in absolute magnitude between the SPD data and the ground-based observations. The ideal value of ME and RSME is 0. RB, *R*, ME, and RMSE were computed using the following equations (Ebert, 2007; C.-Y. Liu et al., 2020; Tang et al., 2016):

$$BR = \frac{\sum S_i}{\sum G_i} \tag{1}$$

$$R = \frac{\sum_{i=1}^{N}\left(S_i - \overline{S}\right)\left(G_i - \overline{G}\right)}{\sqrt{\sum_{i=1}^{N}\left(S_i - \overline{S}\right)^2}\sqrt{\sum_{i=1}^{N}\left(G_i - \overline{G}\right)^2}} \tag{2}$$

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

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

where S_i represents a satellite rainfall estimate, G_i represents the corresponding ground-based rainfall measurement, $\overline{S}$ indicates the average of the satellite rainfall estimates, $\overline{G}$ represents the average of the ground-based rainfall measurements, N represents the total number of data points, and i represents the number of the sample.

The second statistical category was volumetric indices, which represent the ability of SPDs to detect an accurate/inaccurate amount of rainfall. This category includes volumetric hit index (VHI), volumetric false alarm ratio (VFAR), and volumetric critical success index (VCSI). VHI can be expressed as the volume of rainfall accurately detected by the satellites relative to the volume of rainfall accurately detected by the satellites and the missing observations. VFAR represents the volume of false rainfall detected by the SPDs relative to the sum of rainfall detected by the SPDs. VCSI represents the overall measure of volumetric performance. VHI, VFAR, and VCSI range from 0 to 1, with the ideal score for VHI and VCSI being 1 and the ideal score for VFAR being 0. The equations for the volumetric indices are as follows (Aghakouchak & Mehran, 2013; Ayehu et al., 2018; C.-Y. Liu et al., 2020):

$$VHI = \frac{\sum_{i=1}^{N}(S_i \mid (S_i > t \& G_i > t))}{\sum_{i=1}^{N}(S_i \mid (S_i > t \& G_i > t)) + \sum_{i=1}^{N}(G_i \mid (S_i \le t \& G_i > t))} \tag{5}$$

$$VFAR = \frac{\sum_{i=1}^{N} (S_i | (S_i > t \& G_i \leq t))}{\sum_{i=1}^{N} (S_i | (S_i > t \& G_i > t)) + \sum_{i=1}^{N} (S_i | (S_i > t \& G_i \leq t))} \quad (6)$$

$$VCSI = \frac{\sum_{i=1}^{N} (S_i | (S_i > t \& G_i > t))}{\sum_{i=1}^{N} (S_i | (S_i > t \& G_i > t)) + \sum_{i=1}^{N} (G_i | (S_i \leq t \& G_i > t)) + \sum_{i=1}^{N} (S_i | (S_i > t \& G_i \leq t))} \quad (7)$$

where t represents the threshold value of 15 mm/3 hr. This rainfall threshold was defined to represent the ability of SPDs in detecting heavy rainfall events.

4. Results and Discussion

The ability of the SPDs to estimate rainfall during heavy precipitation events caused by typhoons was evaluated in terms of rain rate intensity, elevation, and wind velocity by using continuous statistics (i.e., BR, R, ME, and RMSE) and volumetric indices (i.e., VHI, VFAR, and VCSI). High R, VHI, and VCSI values; low ME, RMSE, and VFAR values; and BR values close to 1 indicated a high-performance level.

4.1. Performance of SPDs During Typhoon Events

The agreement between the rain gauge observations and the satellite rainfall data sets for each typhoon event was determined by using the scatter plots in Figure 2. In general, in all typhoon events, the satellite rainfall data set exhibited strong agreement with the rain gauge observations at low rainfall rates, and this agreement decreased with increasing rainfall rates. According to the R values, the IMERG data set exhibited stronger agreement with the rain gauge observations (0.57–0.68) than did the GSMaP (0.30–0.57) and PERSIANN (0.42–0.51) data sets for almost all the typhoons (Sarika, Haima, Nock-ten, Doksuri, and Mangkhut). C. Huang et al. (2019) revealed that the R value for the IMERG Early Run version 5 data set was approximately 0.38–0.57 for six typhoon events in southern China. The current study confirmed that the latest version of the IMERG data set exhibits increased agreement with the rain gauge observations for higher R values. Consistent with the current result, IMERG version 6 performs better than IMEGR version 5 to represent spatial characteristics of warm-season rainfall over Taiwan at different temporal scales (W.-R. Huang et al., 2020). This might be due to upgrading the morphing algorithm from version 5 to version 6 (W.-R. Huang et al., 2020).

Table 3 presents a summary of the overall quantitative evaluation of the SPDs and rain gauge measurements during the five typhoon events. The statistic metric summary indicates that the three satellite rainfall data sets exhibited different behaviors. This result might have been caused by the spatial-temporal resolution difference, region consideration, climate regime, season, the diverse topographic conditions, the density of rain gauge station distribution, complex typhoon structures, different tracks of the typhoons, the structure of the atmosphere, and heterogeneous rainfall conditions on the spatiotemporal scale (Beck et al., 2019, 2020; Brunetti et al., 2018, 2021; Filho et al., 2022; C. Huang et al., 2019). The GSMaP data set substantially overestimated rainfall for all typhoon events compared with the rain gauge data, yielding positive and greater than 1 of both ME (1.35–18.58 mm/3 hr) and BR values (1.28–1.86). A previous study found that GSMaP also overestimated the daily extreme precipitation over the Western Himalayas (Parida et al., 2017). Both the IMERG and PERSIANN data sets underestimated rainfall compared with the rain gauge data, yielding negative ME and BR values almost for all typhoon events, except for the Nock-ten typhoon. The underestimation of the IMERG data set in this study is in agreement with the findings of other studies that have applied this data set to evaluate rainfall in southern China during typhoons Mawar, Pakhar, Hato, and Merbok on a cumulative scale (C. Huang et al., 2019). In this study, the IMERG data set outperformed the GSMaP and PERSIANN data sets in terms of ME, BR, and RMSE for all typhoon events except the Sarika and Haima typhoon, for which the ME and BR of the IMERG data set were slightly higher than those of the PERSIANN data set.

In terms of the ability of the SPDs to detect heavy precipitation events, the GSMaP data set achieved the highest scores for VHI but the lowest scores for VFAR. The IMERG data set achieved the highest scores for VFAR and VCSI for all typhoon events except the Haima typhoon. The PERSIANN data set achieved the highest scores for VFAR and VCSI during the Haima typhoon. To demonstrate the performance of three SPDs more compre-

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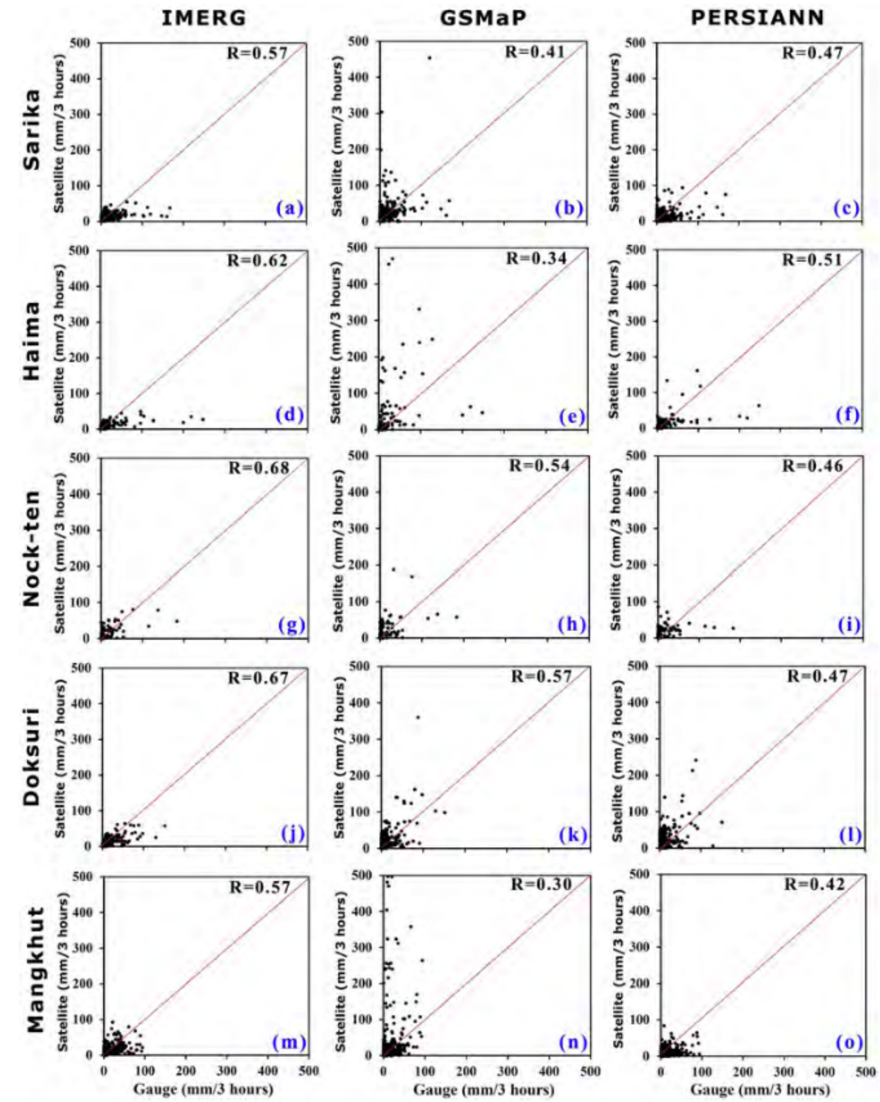

Figure 2. Scatter plot of rain gauge measurements for different satellite precipitation data sets (IMERG, GSMaP, and PERSIANN) during the five typhoon events: Sarika (a–c), Haima (d–f), Nock-ten (g–i), Doksuri (j–l), and Mangkhut (m–o). The parameter *R* represents the correlation coefficient.

hensively, Figure 3 presents a performance diagram that displays an overview of the statistics that indicate how well the three SPDs detected heavy precipitation events caused by typhoons in terms of VHI, VFAR, VCSI, and BR. Such a performance diagram was proposed by Roebber to create a visual framework of the association among multiple aspects of model performance (Roebber, 2009). VHI is represented on the *y*-axis; success ratio (1 − VFAR) is represented on the *x*-axis; BR is represented by the dotted lines beginning at the origin, where the diagonal dotted line represents no bias; and VCSI is represented by the dashed contour lines. The best performance is in the top right corner of the diagram and along the diagonal dotted line, where BR is 1. The IMERG data set achieved the best performance among the SPDs during typhoons Sarika, Nock-ten, Doksuri, and Mangkhut, while the PERSIANN data set achieved the best performance during the Haima typhoon. This result

Table 3
Statistical Metric Summary of the Integrated Merged MultisatellitE Retrievals for Global Precipitation Measurement (IMERG), Global Satellite Mapping of Precipitation (GSMaP), and Precipitation Estimation From Remotely Sensed Information Using Artificial Neural Networks (PERSIANN) Data Sets for the Five Typhoon Events

Name of typhoon	SPD	BR	*R*	ME	RMSE	VHI	VFAR	VCSI
Sarika	IMERG	0.84	0.57	−1.39	32.02	0.52	0.38	0.39
	GSMaP	1.72	0.41	6.13	140.89	0.86	0.52	0.44
	PERSIANN	0.98	0.47	−0.17	3.85	0.45	0.53	0.30
Haima	IMERG	0.73	0.62	−9.36	34.28	0.59	0.20	0.51
	GSMaP	1.28	0.34	18.58	76.03	0.89	0.31	0.64
	PERSIANN	0.97	0.51	−5.82	33.81	0.78	0.20	0.66
Nock-ten	IMERG	1.23	0.68	0.78	13.98	0.84	0.33	0.59
	GSMaP	1.40	0.54	1.35	17.29	0.80	0.43	0.50
	PERSIANN	1.43	0.46	2.93	19.55	0.80	0.44	0.49
Doksuri	IMERG	0.86	0.67	−2.10	16.65	0.61	0.30	0.50
	GSMaP	1.48	0.57	7.84	29.74	0.76	0.48	0.45
	PERSIANN	1.53	0.47	8.78	30.15	0.74	0.51	0.42
Mangkhut	IMERG	0.78	0.57	−0.72	13.59	0.56	0.28	0.46
	GSMaP	1.86	0.30	15.34	61.52	0.84	0.54	0.42
	PERSIANN	0.51	0.42	−1.94	15.03	0.30	0.45	0.24
All Typhoon	IMERG	0.89	0.62	−2.56	22.10	0.62	0.30	0.49
	GSMaP	1.55	0.43	9.85	65.09	0.83	0.45	0.49
	PERSIANN	1.08	0.47	0.76	20.48	0.61	0.43	0.42

Note. Unit of the mean error (ME) and root mean square error (RMSE): mm/3 hr.

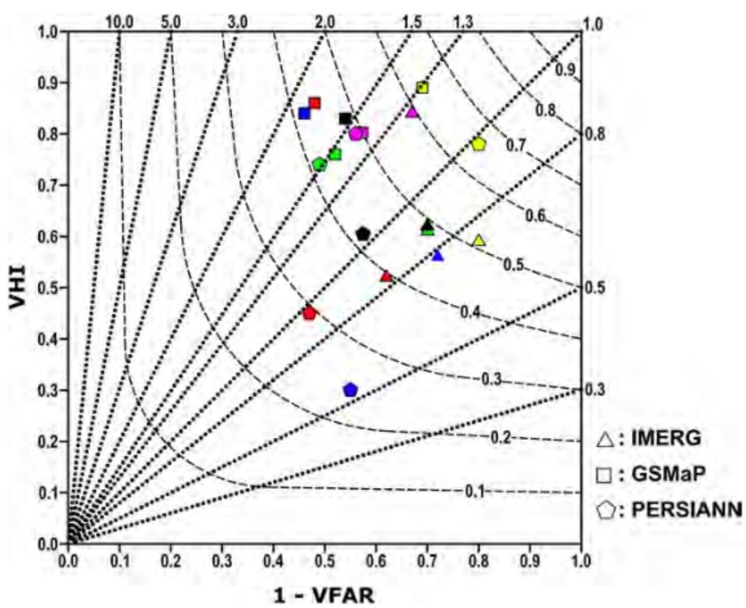

Figure 3. Performance diagram for the satellite precipitation data sets (SPDs) that represents their ability to detect rainfall during typhoon events. Different colors represent different typhoon events (red: Sarika; yellow: Haima; magenta: Nock-ten; green: Doksuri; blue: Mangkhut; and black: all typhoons).

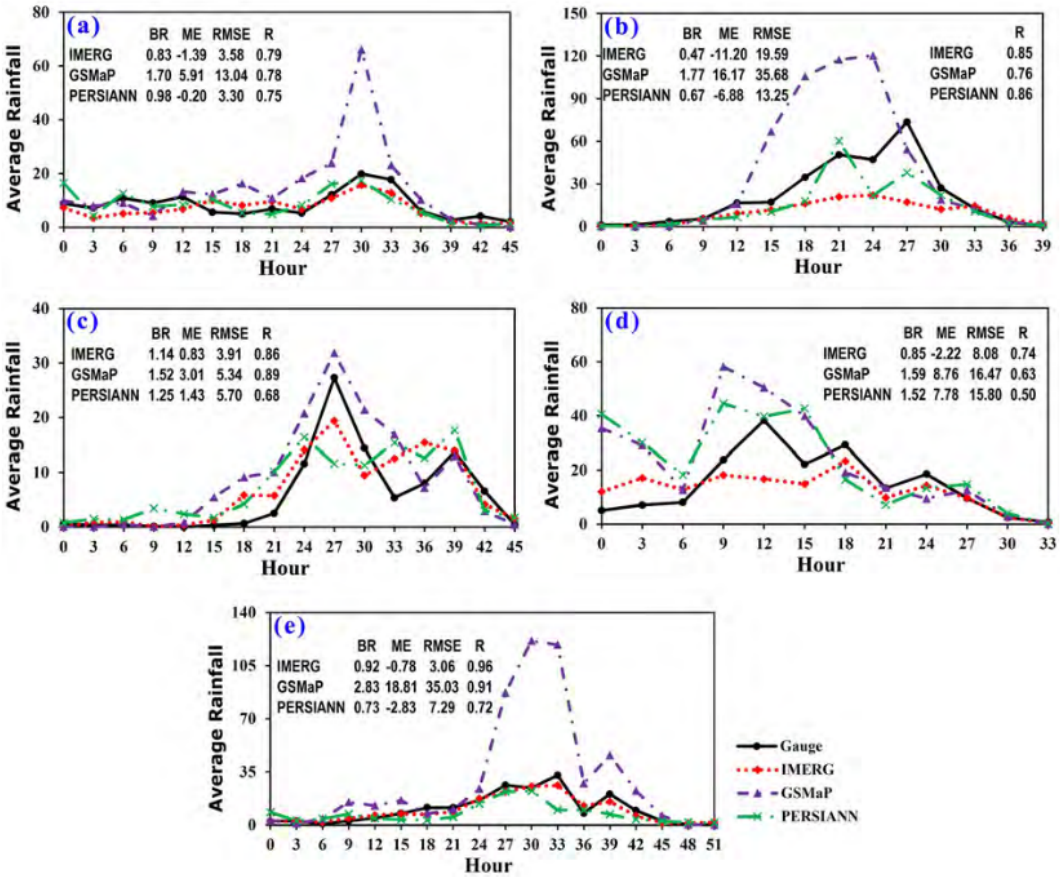

Figure 4. Average 3-hr rainfall during the five typhoon events: (a) Sarika, (b) Haima, (c) Nock-ten, (d) Doksuri, and (e) Mangkhut. Unit of ME and RMSE: mm/3 hr.

can probably be attributed to the high temporal resolution of the IMERG data set when determining the frequency of precipitation events, which allows this data set to detect the regional variance in sub-daily precipitation more effectively (Dezfuli et al., 2017; C.-Y. Liu et al., 2020).

The temporal variation in rainfall is a critical factor in the assessment of extreme weather phenomena and the hydrological cycle (C. Huang et al., 2019; C.-Y. Liu, Kuo, et al., 2016; C.-Y. Liu, Li, et al., 2016). Heavy rainfall in a short period can cause natural disasters, such as floods and landslides. Figure 4 presents plots of the average 3-hr rainfall in the Philippines during the five typhoon events. In general, the IMERG captured the best performance of time series average rainfall with the rain gauge observation during typhoons Nock-ten, Doksuri, and Mangkhut, with the highest scores for BR, ME, and RSME. However, during the Sarika and Haima typhoons, the PERSIANN data set exhibited better performance when capturing the temporal variation of precipitation. The IMERG data set has the highest *R* value during typhoons Sarika, Doksuri, and Mangkhut (0.79, 0.74, and 0.96), while GSMaP dan PERSIANN has scored for R during Nock-ten typhoon (0.89), and Haima typhoon (0.86), respectively. The highest values for average 3-hr rainfall were different for each typhoon event probably due to the differences in atmospheric conditions and the complexity of the typhoon structure. The GSMaP data set exhibited an overestimate with the rainfall station observations during peak rainfall. However, the IMERG and PERSIANN data sets considerably underestimated rainfall during rainfall peaks in the typhoon events.

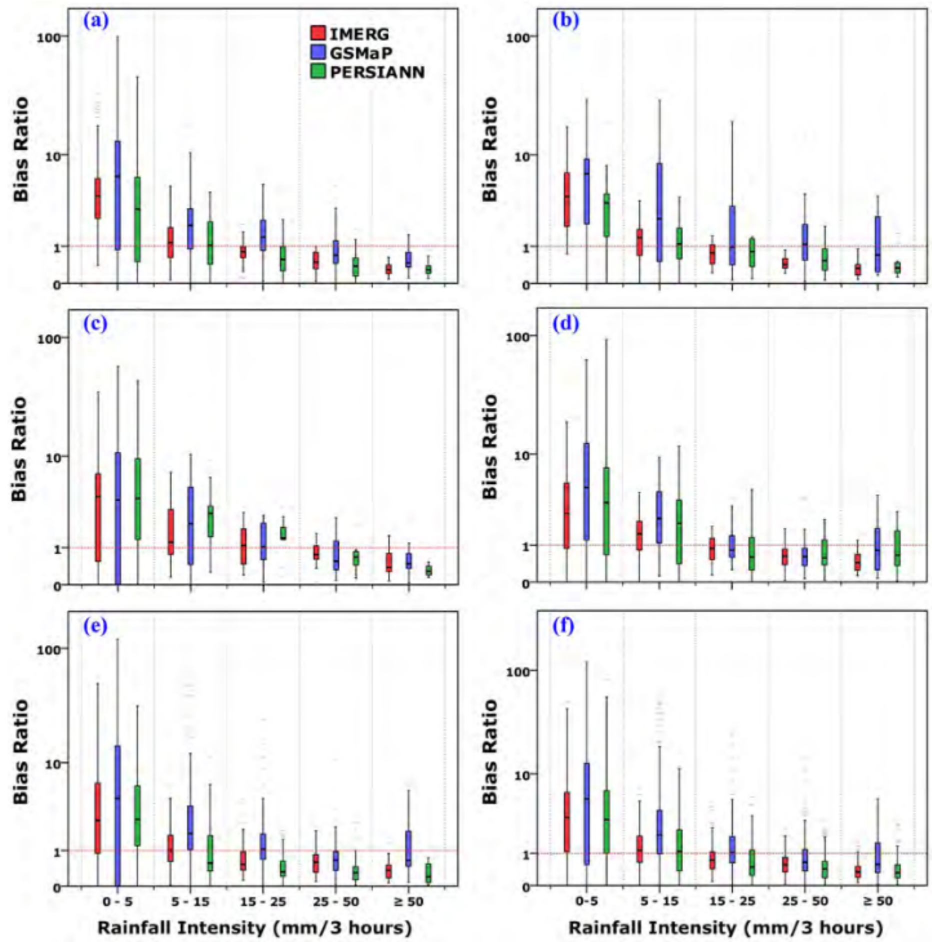

Figure 5. Boxplot of the bias ratios (BRs) for different rainfall intensities for the IMERG, GSMaP, and PERSIANN data sets during the typhoon events: (a) Sarika, (b) Haima, (c) Nock-ten, (d) Doksuri, (e) Mangkhut, and (f) all typhoons.

4.2. Performance of SPDs Under Different Rainfall Intensities

The BR values between the rain gauge station measurements and the data of the IMERG, GSMaP, and PERSIANN data sets for different rainfall rate intervals were derived. Figure 5 presents a boxplot of the BRs for the IMERG, GSMaP, and PERSIANN data sets during the five typhoon events under different rainfall intensities. The bottom and top of the boxplot represent the first and the third quartiles of the data, respectively. The line inside the boxplot represents the second quartile and median. The maximum and minimum values of the data are represented by the lines at the top and bottom of the whisker, respectively. Outliers are any line not within the whisker. The data sets tended to overestimate rainfall during light to moderate rain (0–5 and 5–15 mm/3 hr) and tended to underestimate rainfall during heavy to extreme rain (15–25, 25–50, and >50 mm/3 hr). This result is consistent with those of other studies, one of which confirmed that the IMERG and GSMaP data sets overestimate the frequency of light to moderate rainfall events (1–10 mm) and underestimate the frequency of extreme rainfall events (>0 mm) (C.-Y. Liu et al., 2020). Another study revealed that the GSMaP and PERSIANN data sets underestimate the frequency of extreme rainfall (75–100 mm/day) (Palharini et al., 2020). Fang et al. (2019) discovered that the IMERG data set underestimates extreme precipitation. The underestimation of the SPDs during heavy to extreme rainfall might be caused by the interpolation process of classifying heavy rainfall (Fang et al., 2019). The IMERG data

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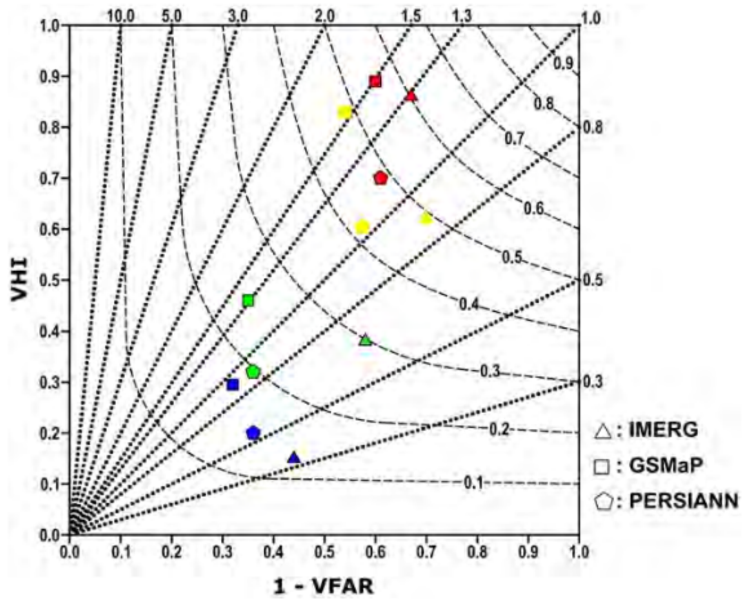

Figure 6. Performance diagram of the satellite precipitation data sets (SPDs) at different threshold values. Different colors represent different threshold values (red: 5 mm/3 hr; yellow: 15 mm/3 hr; green: 25 mm/3 hr; and blue: 50 mm/3 hr).

set exhibited a satisfactory ability to detect moderate rainfall events (5–15 mm/3 hr), whereas the GSMaP data set exhibited superior performance to the other two data sets in detecting heavy to extreme rainfall (15–25, 25–50, and >50 mm/3 hr) during the five typhoon events in the Philippines.

The performance of the SPDs was also assessed at various rainfall thresholds: 5, 15, 25, and 50 mm/3 hr Figure 6 presents the performance diagram for the IMERG, GSMaP, and PERSIANN data sets in terms of the volumetric indices (VHI, 1 − VFAR, VCSI, and BR) for 3-hr precipitation under various rainfall thresholds. The ability of these three SPDs to detect precipitation decreased with an increase in rainfall. VHI and VCSI decreased and VFAR increased with increasing rainfall intensity. These results indicated that the satellite sensors performed poorly in terms of detecting precipitation in extreme rainfall events (Filho et al., 2022; C. Huang et al., 2019; Sun et al., 2016). The IMERG data set exhibited a stronger rainfall detection ability than did the other two data sets when the rainfall was 5, 15, and 25 mm/3 hr. However, the GSMaP data set exhibited the strongest ability to detect rainfall when the rainfall was 50 mm/3 hr. The PERSIANN data set exhibited the weakest ability to detect rainfall at all rainfall rates. Research demonstrated that the PERSIANN data set did not perform well in the detection of daily moderate rainfall events (10 mm) and daily heavy rainfall events (25 mm) in the Wei River Basin in China (J. Liu et al., 2019). The poor performance of the PERSIANN data set may be due to the fact that the precipitation estimation algorithm of PERSIANN is mainly used infrared imagery, which has an indirect correlation with precipitation if compared with IMERG and GSMaP that merge the PMW and infrared imagery to estimate the rainfall value.

4.3. Performance of the SPDs at Different Elevations

The variation in rainfall in the island area is caused by orographic uplift and the complexity of topography (Lee et al., 2014). Topography has a prominent effect on precipitation (C. Chen et al., 2020). The altitudes of the rain gauge stations used in this study were divided into two categories: ≤1,000 m (low altitude) and >1,000 m (high altitude). Table 4 presents an assessment of statistical metrics for the IMERG, GSMaP, and PERSIANN data sets for 3-hr precipitation estimates at different elevations. According to the BR and ME values, the IMERG data set tended to underestimate rainfall at low and high elevations, while GSMaP tended to overestimate rainfall at

Table 4
Statistical Metric Summary of the IMERG, GSMaP, and PERSIANN Data Sets at Different Elevations

Elevation	SPD	BR	*R*	ME	RMSE	VHI	VFAR	VCSI
Low	IMERG	0.94	0.58	−1.34	17.20	0.63	0.33	0.48
	GSMaP	1.73	0.34	10.13	46.95	0.83	0.50	0.46
	PERSIANN	1.04	0.45	0.39	20.69	0.55	0.47	0.37
High	IMERG	0.27	0.77	−11.70	23.92	0.27	0.00	0.27
	GSMaP	1.06	0.79	9.71	35.02	0.92	0.09	0.84
	PERSIANN	0.48	0.67	−9.58	21.90	0.48	0.00	0.48

Note. Unit of ME and RMSE: mm/3 hr.

both elevations. The PERSIANN tended to overestimate rainfall at low elevations but underestimated rainfall at high elevations. The IMERG data set had the highest *R* and lowest RMSE values at low altitudes. The IMERG data set exhibited superior performance at low altitudes because it had the best scores in the continuous statistical analysis (BR, *R*, and RMSE), but it was worse at high altitudes. This might be due to the characteristics of microwave radiometers differing significantly between coastal and terrestrial areas. The distribution of rain gauges is few in the terrestrial area compared to the coastal area. The BR of the GSMaP data set being 1.06 at high altitudes, which indicates that this data set had a 6% bias compared with the rain gauge measurements. The high score BR and *R* of the GSMaP data set at high elevations were possibly caused by the inclusion of the elevation data set derived from the Shuttle Radar Topography Mission 30 Arc Second to classify orographic and non-orographic rainfall (Yamamoto & Shige, 2015).

Satellite rainfall estimates performed better in detecting heavy precipitation at high altitudes than at low altitudes. This result might have been caused by orographic uplift (Tang et al., 2018). In terms of the ability of SPDs to detect heavy rainfall at different elevations, the PERSIANN data set exhibited the lowest VHI and VCSI values at low altitudes, whereas the GSMaP data set exhibited the worse VFAR values at low elevations (Table 4). The GSMaP data set exhibited the highest VHI at both altitudes; the IMERG data set exhibited the best VFAR values at low altitudes, and the IMERG and PERSIANN data set had a perfect VFAR value at high altitudes. The performance diagram summarizes the three SPDs' ability to detect heavy rainfall accurately at different altitudes (Figure 7). The GSMaP data set outperformed the other data sets in terms of the ability to detect heavy rainfall at high elevations, whereas the IMERG data set outperformed the other data sets at low elevations. The PERSIANN data set performed poorly at both elevations probably because its rainfall estimation algorithm does not contain a terrain component (Nguyen et al., 2018).

4.4. Performance of the SPDs Under Different Wind Velocities

The levels of infrastructural and environmental damage caused by typhoon events are influenced by wind intensity. High wind intensity is also associated with heavy rainfall, which is another hazard of typhoon events (Bloemendaal et al., 2020). Wind vectors are one of the variables that were used to forecast the rainfall caused by a typhoon (Kidder et al., 2005). In this study, the wind vector components u and v from the ECMWF at a height of 10 m above the surface, which is observed at the considered rain gauge stations, were processed into wind speed and direction, respectively. The frequency distribution indicates the relationship between wind speed and the continuous performance statistics (Figure 8). The IMERG and PERSIANN data sets underestimated rainfall compared with the gauge station measurements, yielding a high-frequency concentration of negative MEs (−20 to 0 mm/3 hr) and a BR below 1 for the distribution of wind speed. The GSMaP data set tended to overestimate rainfall, with a distribution of frequency concentrated on positive MEs (0–30 mm/3 hr) and a BR above 1. The IMERG data set exhibited superior agreement with the rain gauge observations at different wind speeds, with the dominant distribution frequency of *R* ranging from 0.4 to 1 and a few ranging from 0.1 to 0.2. For the PERSIANN and GSMaP data sets, the distribution frequency of *R* ranged from 0 to 0.9. The frequency distributions of RMSE at each wind speed for the IMERG and PERSIANN data sets ranged from 0 to 30 mm/3 hr, whereas those for the GSMaP data set ranged from 0 to 50 mm/3 hr. Among the three SPDs, the IMERG data set was the most consistent with the rain gauge measurements in terms of having

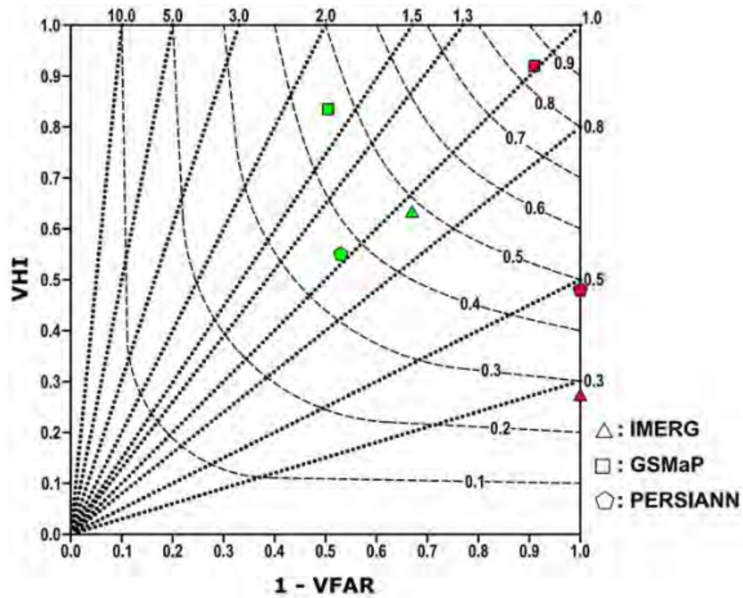

Figure 7. Performance diagram of the satellite precipitation data sets (SPDs) at different altitudes. Different colors represent different altitudes (green: low altitude and red: high altitude).

the most continuous statistical parameters at the different wind speeds. The distribution frequencies of ME, RMSE, *R*, and BR for the IMERG data set were concentrated around the near-perfect value for the continuous statistics.

The distribution percentage of each volumetric index presented in Figure 9 was used to describe the association between wind speed and the ability of the SPDs to detect heavy rainfall events caused by typhoons. In terms of the VHI distribution, the GSMaP data set exhibited the best performance, followed by the IMERG and PERSIANN data sets. The all SPDs data set yielded a high-frequency distribution for a VHI range of 0.9–1.0 in the wind speed range of 4.5–6 m/s. In terms of false rainfall estimates, the IMERG data set outperformed the GSMaP and PERSIANN data sets. The IMERG data set had a high-frequency distribution at a lower VFAR than did the other SPDs. The comprehensive evaluation of the volumetric index performance indicates that compared with the other SPDs, the IMERG data set exhibited a stronger ability to detect heavy rainfall at various wind speeds.

The complex topography and mountainous regions with orographic convection and low-troposphere winds represent a challenge in rainfall estimation by satellites (Shige et al., 2013). Luzon, which is located in the northern part of the Philippines, has a complex and mountainous topography and often experiences typhoons. Therefore, the influence of wind in mountainous areas on the performance of satellite rainfall estimations must be studied. Wind direction and speed data were collected from a selected rainfall measurement station on Luzon island (Figure 1b) and analyzed in the form of wind roses. A wind rose is a graph that represents the distribution of wind speed and direction for an area over a certain period. Figure 10a presents a wind rose for the eastern part of the mountainous region, and Figure 10k presents a wind rose for the western part of the region. A total of 58% of the winds are in the south direction in the eastern part of the mountainous region, and the most frequent wind speed interval is 0–3 m/s, which accounts for 42% of the wind speeds. In the eastern part of the mountainous region, wind speed is primarily in the intervals of 0–3 and 3–6 m/s. A total of 46% of the winds in the western part of the mountainous region are in the north direction, and the predominant wind speed is >15 m/s, which accounts for 12% of the wind speeds. In the western part of the mountainous region, wind speed is predominantly in the intervals of >15, 12–15, 9–12, and 6–9 m/s. This finding indicates that wind speeds are higher in the western part of the mountainous region than in its eastern part. The wind velocity will change depending on the path of the typhoon and the characteristics of topographic, and rainfall intensities will change accordingly.

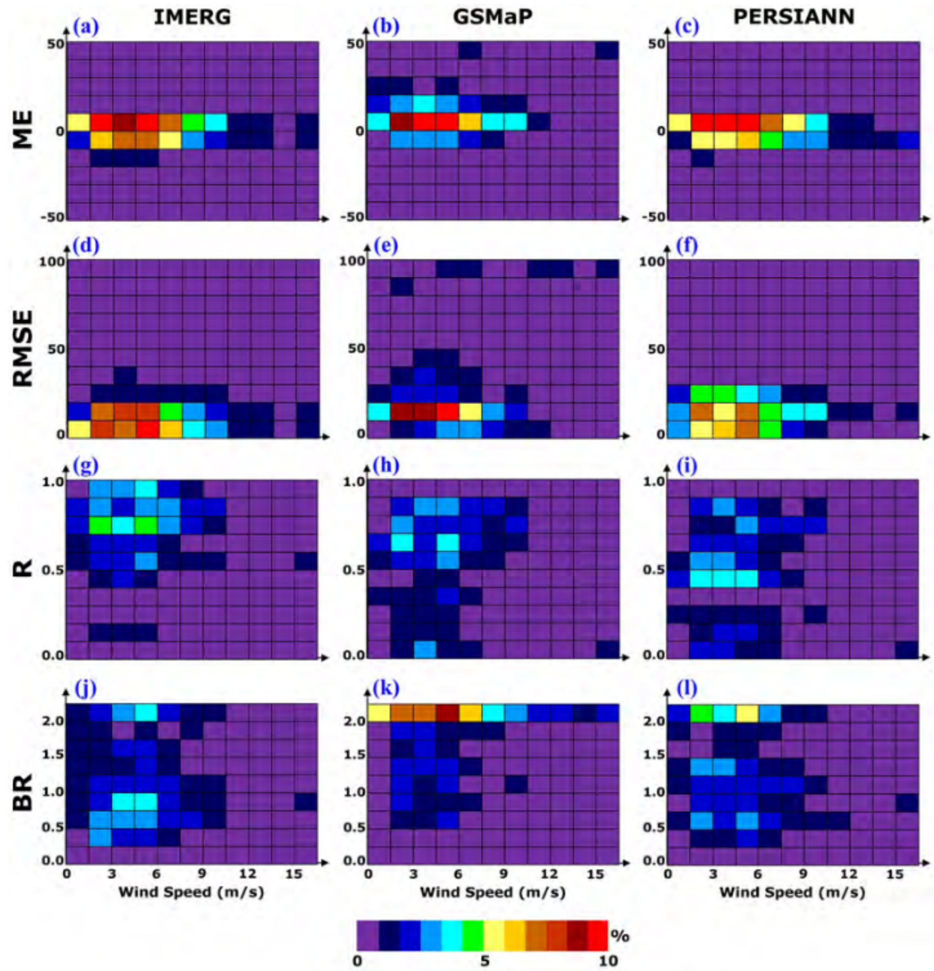

Figure 8. Distribution percentage of each continuous statistic for the IMERG, GSMaP, and PERSIANN data sets at different wind speeds: (a–c) ME, (d–f) RMSE, (g–i) R, and (j–l) BR. The ME and RMSE value are presented in mm/3 hr.

Figures 10b–10j) depict the distribution of volumetric statistical values for the different wind direction and wind speed ranges in the eastern part of the mountainous region of Luzon. Figures 10l–10t) illustrate the distribution of volumetric statistical values for the western part of the mountainous region. The GSMaP data set outperformed the other SPDs in detecting heavy rainfall events in the eastern part of the mountainous region, as indicated by the distributions of VHI, VFAR, and VCSI. Compared with the other SPDs, the GSMaP data set exhibited superior distributions of VHI, VFAR, and VCSI under almost all ranges of wind speed and wind direction. The GSMaP data set yielded high VHI values for most wind speed ranges and wind directions in the western part of the mountainous region. This result indicated that the GSMaP data set exhibited a strong performance in detecting heavy rainfall events under high wind speeds. However, the VFAR values of the GSMaP data set were higher than those of the other SPDs, which were approximately 0.5–0.9 for the western part of the mountainous area. This result indicates that the GSMaP algorithm generates a large quantity of false rainfall data under high wind speeds. Among the three SPDs, the GSMaP data sets demonstrated a stronger ability to detect heavy rainfall events in terms of the effect of wind velocity in the western and eastern parts of the mountainous region. The better performance of GSMaP might be due to the inclusion of horizontal surface wind from the GANAL

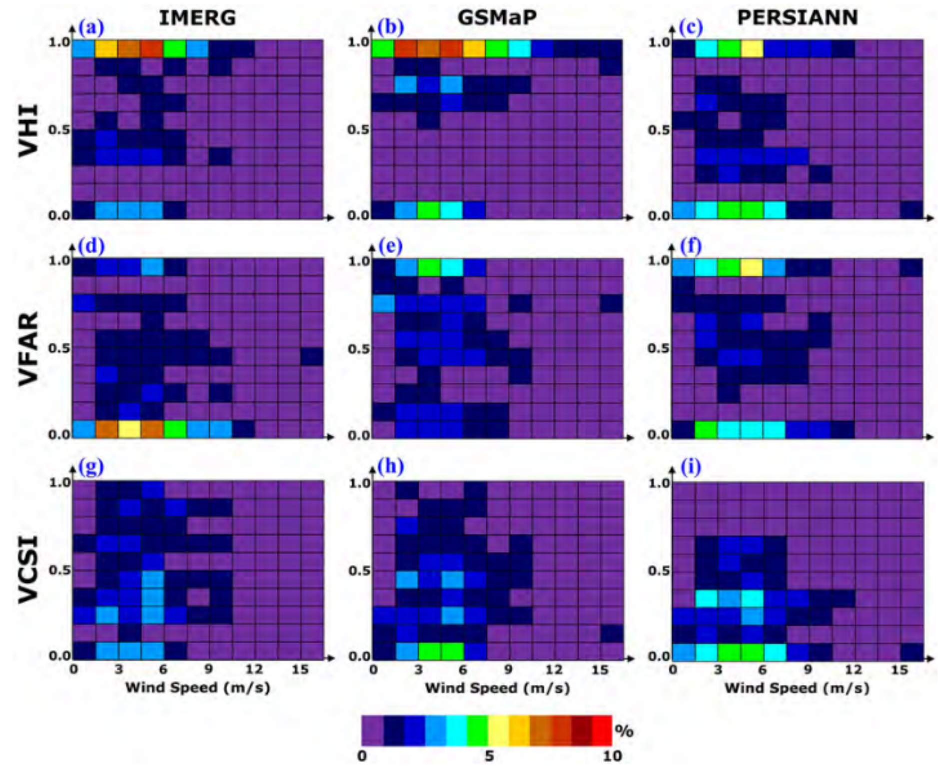

Figure 9. Distribution percentage of each volumetric index for the IMERG, GSMaP, and PERSIANN data sets at different wind speeds: (a–c) volumetric hit index (VHI), (d–f) volumetric false alarm ratio (VFAR), and (g–i) volumetric critical success index (VCSI).

data in the GSMaP microwave radiometers algorithm to classify the orographic or non-orographic precipitation (Yamamoto & Shige, 2015).

5. Conclusions

Assessing the performance of SPDs during heavy precipitation caused by typhoons is crucial for utilizing them and evaluating their algorithms. Studies have analyzed the ability of SPDs to detect heavy precipitation caused by typhoon events on daily, monthly, seasonal, annual, and cumulative scales. This study performed a sub-daily (3-hr) assessment of the performance of three near-real-time SPDs, namely the IMERG, GSMaP, and PERSIANN data sets, during five typhoon-related heavy precipitation events in the Philippines between 2016 and 2018. This assessment was performed through a point-to-grid comparison by using continuous and volumetric statistical validation indices to assess the R34 values of the typhoons, rainfall intensity, terrain, and wind velocity effects. This study yielded the following results:

1. The IMERG data set exhibited good agreement with the rain gauge observations and performed considerably well in detecting rainfall during the five typhoon events over the Philippines. The GSMaP data set exhibited an overestimate with the rainfall station observations during peak rainfall, while the IMERG and PERSIANN data sets considerably underestimated rainfall.
2. The precipitation data sets tended to overestimate rainfall in light to moderate rainfall events and underestimate rainfall in heavy to extreme rainfall events. The IMERG data set exhibited a strong ability to detect rainfall in moderate rainfall events (5–15 mm/3 hr), whereas the GSMaP data set exhibited superior performance in detecting rainfall during heavy to extreme rain events (15–25, 25–50, and >50 mm/3 hr) during the five typhoon events in the Philippines.

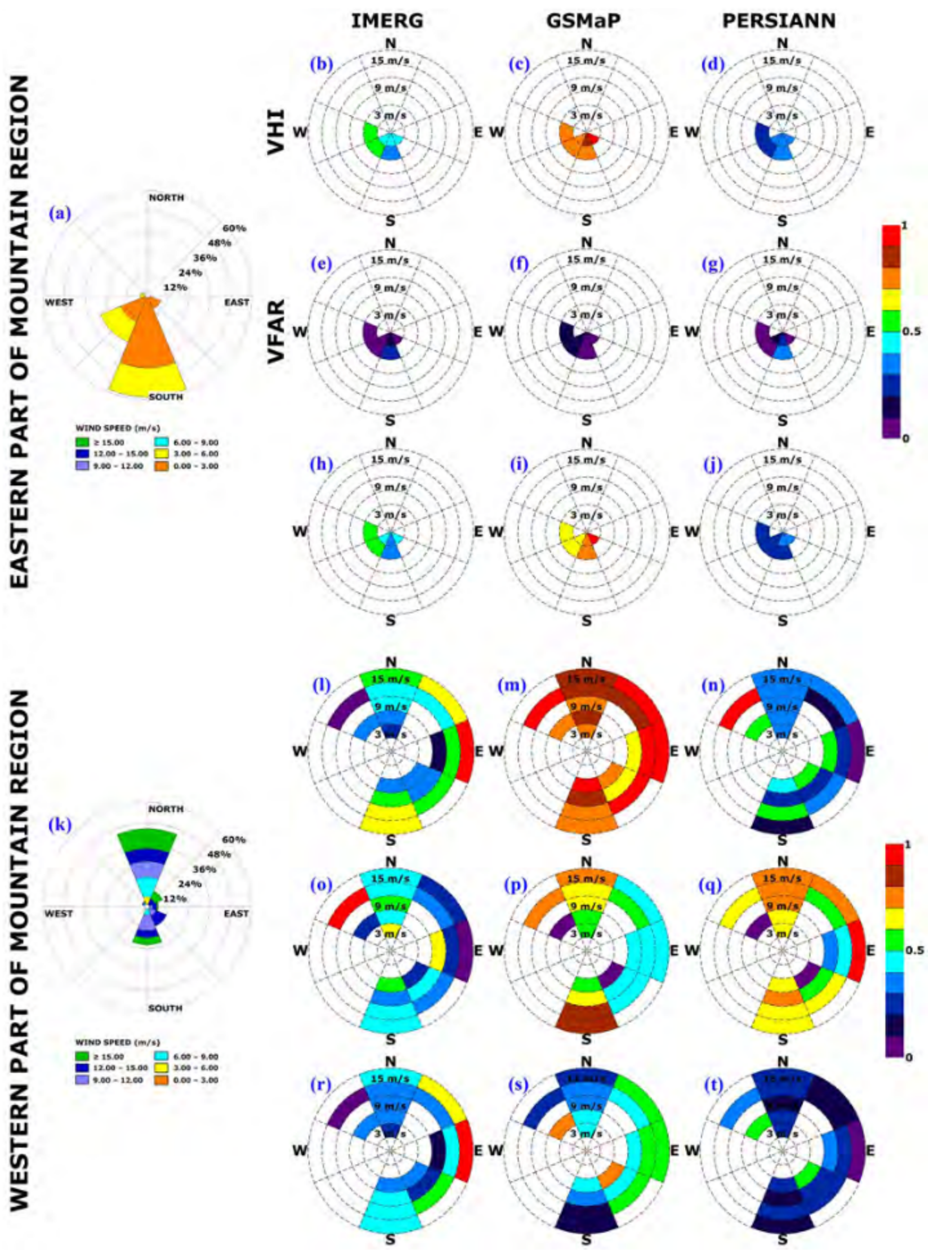

Figure 10. Three-hour, eight-sector wind rose, and distribution of volumetric indices for the IMERG, GSMaP, and PERSIANN data sets for different wind directions and wind speed ranges on Luzon island: (a) wind rose for the eastern part of the mountainous region, (b)–(d) VHI for the eastern part of the mountainous region, (e)–(g) VFAR for the eastern part of the mountainous region, (h)–(j) VHI for the eastern part of the mountainous region, (k) wind rose for the western part of the mountainous region, (l–n) VHI for the western part of the mountainous region, (o–q) VFAR for the western part of the mountainous region, and (r–t) VHI for the western part of the mountainous region.

3. The GSMaP data set outperformed the other SPDs in terms of the ability to detect heavy rainfall at high elevations, whereas the IMERG data set outperformed the other SPDs in terms of the ability to detect rainfall at low elevations.
4. Wind direction and wind speed influence the ability of SPDs to detect rainfall. The IMERG data set exhibited a strong ability to detect heavy rainfall under various wind speeds. The GSMaP data set exhibited a stronger ability to detect heavy rainfall events in terms of wind velocity in the eastern and western part of the mountainous region over Luzon island.

The accurate detection and estimation of heavy precipitation with SPDs remain a challenge in archipelagos with complex terrain or mountainous areas. In this study, the IMERG and GSMaP data sets demonstrated a promising ability to detect heavy precipitation caused by typhoon events. An in-depth investigation is required before the IMERG and GSMaP data sets are applied to tropical-cyclone-related studies. Developments in SPD algorithms are expected to focus on improving the detection of extreme rainfall and the use of hourly rain gauge observations for calibration. The fusion of SPDs also needs to be considered because the results of the performance analysis of each SPD are different in detecting extreme rainfall, so that a reliable satellite precipitation product is obtained. Additional studies using other typhoon event samples are required to investigate the source of error in SPDs. Future work will involve evaluation of the SPDs with respect to the rain gauge which is the location outside of the R34, wind speed validation, and analyze the effect of vertical velocity.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The authors credit the providers of the IMERG, GSMaP, and PERSIANN data sets. The half-hourly IMERG Early rainfall estimate is published and can be accessed through https://disc.gsfc.nasa.gov/datasets/GPM_3IMERGHHE_06/summary?keywords=%22IMERG%20Early%22. The GSMaP NRT data is freely available after registration in the JAXA G-Portal (https://gportal.jaxa.jp/gpr/). The hourly PERSIANN near-real-time precipitation data set can be downloaded free of charge (https://chrsdata.eng.uci.edu/).

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