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INTERCOMPARISON OF GLOBAL SATELLITE MAPPING OF PRECIPITATION (GSMAP) USING RAIN-GAUGE OBSERVATIONS BASED ON MULTIPLE TEMPORAL RESOLUTIONS IN VIETNAM

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Abstract The performance of the Global Satellite Mapping of Precipitation (GSMaP) data over Vietnam during the period from March 2014 to October 2018 was analyzed by comparing three standard products, including the newest Standard version 7 (MVKv7), the Standard with Gauge-Calibration version 7 (GAUv7), and the Standard with Gauge-Calibration version 6 (GAUv6) at two temporal resolutions (daily and 6-hourly accumulated rainfall) in order to assess the importance of the rain-gauge calibration algorithm as well as to determine whether the upgraded version showed an improved performance over Vietnam. Besides, the effects of the elevation and estimation of GSMaP for several rainfall thresholds also were considered. The results suggested the potential applications of GSMaP MVKv7 for Highland Vietnam, GAUv6 and GAUv7 for other regions, and the utilization of GSMaP for heavy-rainfall cases. However, the argument about the better quality of GAU version 7 than version 6 is still controversial.

Keywords: satellite rainfall, GSMaP, Vietnam, validation

1. Introduction

As humans acknowledge the universe, the Earth is the main planet in our solar system, where life is conceivable in view of the accessibility of water and oxygen. Because water is one of the most essential foundations of life, it is important to understand the characteristics of water as well as water cycle in order to sustainably manage and properly consume it, especially in circumstances in which both human activities and climate change enormously impact water quantity and water quality. Among the abundance of rainfall datasets, determining which products to use is not a simple task. The rain-gauge datasets, which are observed and measured at specific meteorological, hydrological, or even rainfall-measuring stations on the ground, are considered as the initial and the most accurate data. However, these stations are limited and unevenly distributed, making research activities and water management difficult. Therefore, the release of the gridded rainfall data products as well as rainfall estimated from satellites has solved these problems. Over the last two decades, satellite rainfall estimation has become more accepted owing to its advantage in spatial and temporal resolutions. However, unlike the directly measured methodology of rain-gauge data, satellite-based precipitation is achieved based on the optimally combined algorithm of various wavelength-radiation data observed from precipitation-related satellites and precipitation gauge analyses. Besides, satellite estimation is profoundly influenced by the algorithm and the radiation characteristics of satellites. The difference of the estimated magnitude of annual precipitation was said to be up to 300 mm among those datasets (Sun *et al.* 2018). Therefore, a rainfall dataset should be carefully validated before using it to obtain a proper analysis.

With the aim of substituting the successful Tropical Rainfall Measuring Mission (TRMM) satellite, which was operated continuously from 1997 to 2015 (Kubota *et al.* 2020), the Global Precipitation Measurement (GPM) core satellite carrying an active precipitation radar and a passive microwave radiometer was launched in 2014 to work along with a constellation of other satellites to enhance the temporal and spatial resolution of observations, which could serve urgent social demands, such as weather forecasts, water management, etc (Hou *et al.* 2014). Since 2002, the year of the initial stage, to 2014, the year of the birth of the newest version up to now, many evaluations and validations of the GSMaP products have been carried out. Kubota *et al.* (2007) studied the accuracy of the GSMaP_MWR (GSMaP Microwave Radiometer Algorithm) product and reported that the correlation coefficient of the GSMaP with rain-gauge analyses was higher over the ocean and relatively low over the land surface and in summer than in winter. Anonashi *et al.* (2009) proposed an improvement of GSMaP ability to detect rainfall intensity higher than 10 mm/h over oceans and the lower rainfall intensity for lands and coastal areas by using different scattering signals for each surface type and applying look-up tables to estimate precipitation rates. However, GSMaP still had difficulty in detecting rainfall intensity weaker than 2 mm/h over sub-tropical regions. Shige *et al*. (2013) developed an orographic/non-orographic rainfall classification scheme to increase the rainfall estimate of GSMaP over places where shallow orographic rain systems dominated. In Vietnam, GSMaP has been used more frequently not only in scientific studies but also in daily operation in Vietnam. Hence, the assessment of the reliability of these data, especially short-range datasets, is essential for many applications that require specific coverage and short temporal resolution such as flood or cyclone forecasts.

2. Dataset and Methodology

Satellite rainfall dataset

In weather forecasting, not only the knowledge and experience of forecasters play an important role, but the collected observed data source also partly contributes to publishing accurate forecasting bulletins. In order to validate an acceptable product that can be used as a substitute for a ground-based dataset with certain drawbacks, such as its limited quantity, especially in rural areas, and the shortages of real-time observations, this study carried out an intercomparison between the three GSMaP products, namely Standard version 7 (abbreviated as MVKv7) and two Standard with Gauge-Calibration products version 6 and 7 (GAUv6 and GAUv7). In addition, this study determined the effectiveness of the GSMaP calibrating algorithm to standard products applicable to Vietnam, a country with diversified climate conditions due to its unique geographical location and topographic nature. Moreover, after upgrading to the algorithm version 7, improvements were applied in the gauge correction, orographic rainfall classification scheme and weak rain detection over the ocean (Yamamoto *et al.* 2017; Mega *et al.* 2019). Hence, two different versions of the standard-gauge dataset were used to determine whether the newest algorithm of GSMaP product (version 7) could be better than its predecessor. These above products processed the same spatial resolution of 0.1-degree latitude/longitude and a latency of 3 days after the observation.

Table 1 Numerical orders and names of in-situ stations across Vietnam used in this study

No.	Name	No.	Name	No.	Name	No.	Name	No.	Name
1	Muong Te	36	Chiem Hoa	71	Ba Vi	106	Ba Don	141	EaKmat
2	Sin Ho	37	Cho Ra	72	Son Tay	107	Con Co	142	Lac
3	Tam Duong	38	Ngan Son	73	Ha Noi	108	Dong Ha	143	Dac Mil
4	Than Uyen	39	Bac Can	74	Chi Linh	109	Khe Sanh	144	Dac Nong
5	Lai Chau	40	Thai Nguyen	75	Hai Duong	110	Hue	145	Da Lat
6	Tuan Giao	41	Dinh Hoa	76	Hung Yen	111	A Luoi	146	Lien Khuong
7	Pha Din	42	Minh Dai	77	Nam Dinh	112	Nam Dong	147	Bao Loc
8	Dien Bien Phu	43	Phu Ho	78	Van Ly	113	Da Nang	148	Phuoc Long
9	Muong La	44	Viet Tri	79	Phu Ly	114	Tam Ky	149	Dong Phu
10	Son La	45	Vinh Yen	80	Nho Quan	115	Tra My	150	Tay Ninh
11	Song Ma	46	Tam Dao	81	Ninh Binh	116	Ly Son	151	Bien Hoa
12	Co Noi	47	Cao Bang	82	Cuc Phuong	117	Quang Ngai	152	Xuan Loc
13	Yen Chau	48	Bao Lac	83	Thai Binh	118	Ba To	153	Vung Tau
14	Bac Yen	49	Nguyen Binh	84	Hoi Xuan	119	Hoai Nhon	154	Con Dao
15	Phu Yen	50	Trung Khanh	85	Yen Dinh	120	An Nhon	155	Huyen Tran
16	Moc Chau	51	That Khe	86	Sam Son	121	Quy Nhon	156	Moc Hoa
17	Mai Chau	52	Lang Son	87	Bai Thuong	122	Tuy Hoa	157	My Tho
18	Kim Boi	53	Bac Son	88	Thanh Hoa	123	Nha Trang	158	Ba Tri
19	Chi Ne	54	Huu Lung	89	Nhu Xuan	124	Cam Ranh	159	Cao Lanh
20	Lac Son	55	Dinh Lap	90	Tinh Gia	125	Song Tu Tay	160	Cang Long
21	Hoa Binh	56	Mong Cai	91	Quy Chau	126	Truong Sa	161	Chau Doc
22	Lao Cai	57	Quang Ha	92	Tuong Duong	127	Phan Rang	162	Can Tho
23	Bac Ha	58	Tien Yen	93	Quy Hop	128	Phan Thiet	163	Soc Trang
24	Sa Pa	59	Co To	94	Tay Hieu	129	Ham Tan	164	Rach Gia
25	Pho Rang	60	Cua Ong	95	Con Cuong	130	Phu Quy	165	Phu Quoc
26	Mu Cang Chai	61	Bai Chay	96	Quynh Luu	131	Dac To	166	Tho Chu
27	Yen Bai	62	Uong Bi	97	Do Luong	132	Kon Tum	167	Bac Lieu
28	Van Chan	63	Hiep Hoa	98	Hon Ngu	133	Pleiku	168	Ca Mau
29	Luc Yen	64	Luc Ngan	99	Vinh	134	An Khe		
30	Ha Giang	65	Son Dong	100	Huong Son	135	Yaly		
31	Hoang Su Phi	66	Bac Giang	101	Ha Tinh	136	Cheo Reo		
32	Bac Me	67	Bac Ninh	102	Huong Khe	137	Eahleo		
33	Bac Quang	68	Phu Lien	103	Ky Anh	138	Buon Ho		
34	Tuyen Quang	69	Hon Dau	104	Tuyen Hoa	139	MDrac		
35	Ham Yen	70	Bach Long Vi	105	Dong Hoi	140	Buon Me Thuot		

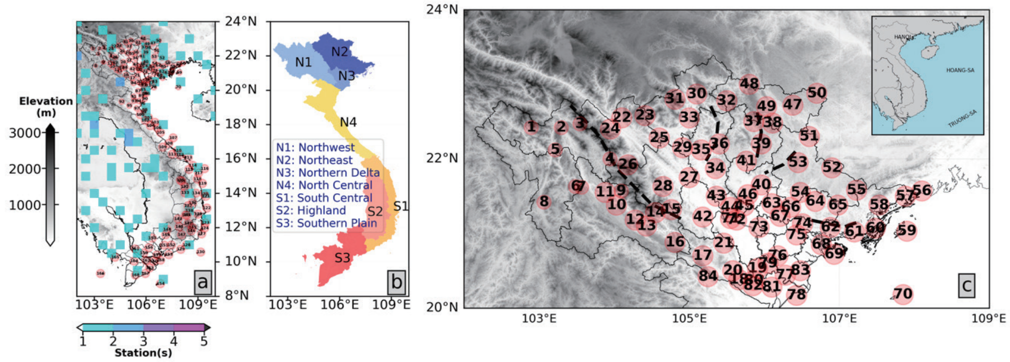

Fig. 1 (a) The maximum number of rain-gauge stations calibrated at each grid of the Climate Prediction Center (CPC) Unified Gauge-based Analysis of Global Daily Precipitation dataset (shown in colored squares), and the in-situ stations used in this study (plotted as red circles with stations' numerical orders in Table 1). The topography map with its gray-scale bar was obtained from the Global Land One-km Base Elevation (GLOBE) dataset. (b) Simulations of seven climatic regions in Vietnam. (c) The larger map of northern Vietnam, including dash lines presenting Hoang Lien Son Mountain Range, Song Gam Arc, Ngan Son Arc, Bac Son Arc, and Dong Trieu Arc from left to right, respectively.

Rain-gauge dataset

The gauge-based rainfall data of 168 out of 186 in-situ stations across Vietnam, collected during the period from March 2014 to October 2018, could be considered as a reliable reference to compare with the performance of other rainfall datasets. This is because these data were officially observed under the principles of the World Meteorological Organization (WMO) and were used for the professional operation works at the National Center for Hydro-meteorological Forecasting Center of Vietnam (NCHMF), the Vietnam Meteorology and Hydrology Administration (VNMHA). With the aim of monitoring the weather and assisting with mitigating weather-related disasters, such as floods, two kinds of short temporal resolutions, including the 6-h accumulated rainfall and daily rainfall data, were analyzed. The names of these in-situ stations are listed in Table 1; and their locations, including the maximum number of rain-gauge stations used at each grid of the Climate Prediction Center (CPC) unified gauge-based analysis of global daily precipitation dataset provided by the National Oceanic and Atmospheric Administration (NOAA), are shown in Fig. 1a. Because the CPC dataset (Chen *et al.* 2008) provided the adjusting values for the GSMaP Standard Gauge Product, the precipitation estimation was also built on the station map of CPC. For Vietnam, the total number of about 29 stations used for the CPC data did not vary significantly during the study period. However, it is important to note the grids calculated by the CPC dataset without any red dots representing 168 stations used in this study. This could emerge from the rainfall measuring stations that were outside the scope of this study or the CPC itself. A topography map was obtained from the Global Land One-km Base Elevation (GLOBE) project with a spatial resolution of 1 km (Hastings and Dunbar 1999). More information about this project could be found at the official website written in the reference. However, the topography datatset was downloaded from the data library of the International Research Institute for Climate and Society, Earth Institute, Columbia University as the following link: https://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NGDC/.GLOBE/topo/datafiles.html. Figure 1b shows a relative simulation of the seven climatic regions of Vietnam mentioned in this study, including the North West (N1), North East (N2), Northern Delta (N3), North Central (N4), South Central (S1), Highland (S2), and Southern Plain (S3) (Nguyen and Nguyen 2004).

Besides, the information about the altitude of the rain-gauge station was also used when considering the effect of topography on the performance of the satellite estimation. Six rainfall thresholds, which are widely used in daily operations at the NCHMF, were applied to evaluate the quality of the GSMaP. These thresholds included (<0.6 mm/day), (≤0.6 mm/day) to (<6 mm/day), (≤6 mm/day) to (<16 mm/day), (≤16 mm/day) to (<50 mm/day), (≤50 mm/day) to (<100 mm/day), and (≥100 mm/day). The respective accumulated precipitation amounts calculated for every 6 h were: (<0.15 mm/6 h), (≤0.15 mm/6 h) to (<1.5 mm/6 h), (≤1.5 mm/6 h) to (<4.0 mm/6 h), (≤4.0 mm/6 h) to (<12.5 mm/6 h), (≤12.5 mm/6 h) to (<25 mm/6 h), and (≥25 mm/6 h).

Statistical Validation

The GSMaP satellite products in this study were evaluated using the following statistical verification parameters: mean error (ME), root mean square error (RMSE), and normalized standard deviation (STDN). The formulas for these statistics are as follows:

$$ME = \frac{1}{N}\sum_{i=1}^{N}(P_i - O_i) \quad (1)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(P_i - O_i)^2}{N}} \quad (2)$$

$$STDN = \frac{STD(P)}{STD(O)} \quad (3)$$

Where P_i is the estimated value of the satellite dataset, O_i is the observed value at time *i*. *N* is the number of the sample. *STD, P,* and *O* stand for standard deviation, satellite dataset and observation respectively.

The longitudes and latitudes of 168 stations were used to calculate the nearest points among the four grid points of the satellite dataset.

3. Results

The general spatial performance of three products

Owing to the complexity of topography as well as the climate conditions, the rainfall patterns vary largely between the seven sub-climate regions of Vietnam (Matsumoto 1997; Nguyen-Le *et al.* 2015). Thus, it is important to validate the GSMaP dataset for the whole country to evaluate its spatial performance.

The discrepancies between the two sets of statistical indices for the three GSMaP products with different temporal resolutions are shown in Figs. 2 and 3. In spite of the same time from March 2014 to October 2018, three daily GSMaP products presented quite different rainfall-estimating performances in which GAUv6 and GAUv7 showed less variation in comparison with MVKv7. However, not much difference was observed between the ME maps of daily and 6-hourly accumulated rainfall data. When considering in detail from the north to the south across the country and focusing only on highly contrast stations (presented in red and blue colors), in the north of Vietnam MVKv7 still overestimated more largely in the N3 region, the northern part of the N4 region and the eastern coast of N2 than the two GAU products in terms of the ME map (Fig. 2). However, common underestimations of the three product sets were observed in the mountainous areas of N1 and N2, although GAUv6 and GAUv7 still shared their similarities in small overestimation (approximately 0.8 mm/day or 0.2 mm/6 h) which was different from MVKv7 (<-0.8 mm/day or <-0.2 mm/6 h). In addition, MVKv7 showed much underestimation at some northwesternmost mountainous stations. The situation was opposite at the central and southern parts of N1 region (along the Hoang Lien Son Mountain Range) for MVKv7 products with small qualities (approximately 0.8 mm/day), while GAUv6 and GAUv7 shared their lower estimation over this area. The higher precipitation estimation over the leeward side of the mountain range was similar to the findings of Nodzu *et al.* (2019) for GSMAP reanalysis standard version 6 and still remained in MVKv7 according to this study. However, this matter was changed in standard with gauge-calibration products (for both GAUv6 and GAUv7). The most common among these three products over the northern regions was the profound negative ME at the Bac-Quang station (at the numerical order of 33 in Table 1 and Fig. 1c, 22.5°N–104.87°E), which was one of the highest annual rainfall-receiving places in Vietnam.

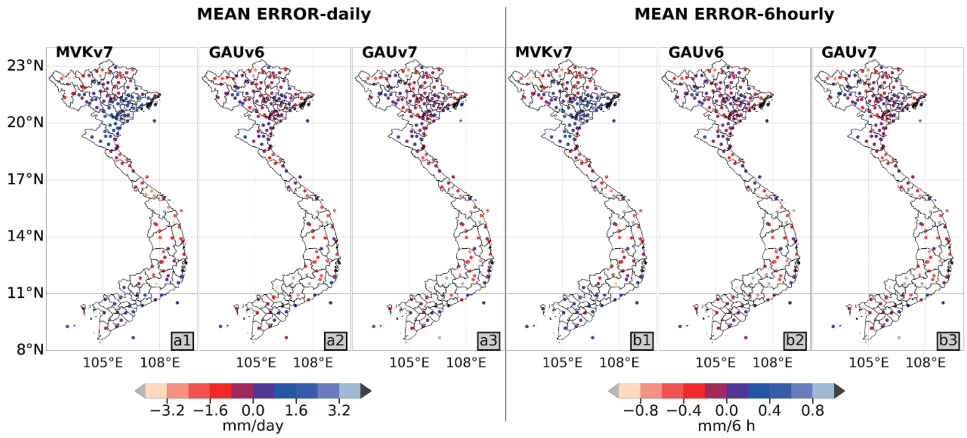

Fig. 2 Mean error of the satellite rainfall estimation (MVKv7, GAUv6 and GAUv7) with the rain-gauge dataset (OBS) for (a1, a2, a3) the daily and (b1, b2, b3) the 6-hourly accumulated rainfall.

The divergence between three products could be mostly seen in the central coastal areas. Including the northernmost part of the N4 region mentioned above, around the latitude of 11.5°–12°N of the S1 region, MVKv7 also tended to overestimate quite differently to the GAUv6 and GAUv7 products. In contrast, MVKv7 and GAUv7 generally underestimated at approximately 16.3°–18°N, while GAUv6 presented a small overestimation (0.8 mm/day). Moreover, the most impressive matter was the low performance of the three products surrounding the 16.3°–18°N region, where they illustrated a homogeneously negative ME with moderate values (less than -0.2 mm/6 h). A similar pattern was observed around 12°N. The above results indicated the “hard-to-handle” complexity in estimating rainfall values for transitional-climate regions. Interestingly, MVKv7 presented less variation in the Highland region (S2), especially in the middle part, compared to the GAUv6 and GAUv7 products. This could be noted that the elevation of the Highland region was higher to the north and the south than the center. This might arise from the gauge-corrected data where calibrated stations were not representative of the

Highland region.

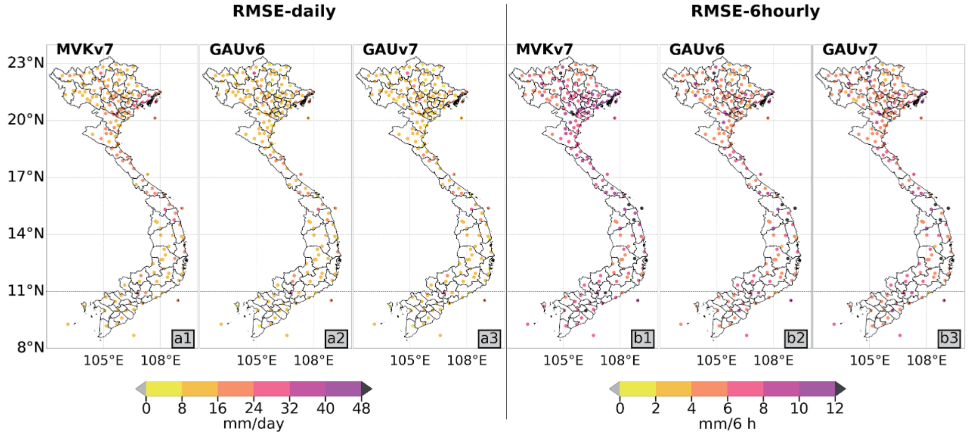

Fig. 3 Root mean square error (RMSE) of the satellite rainfall estimation data (MVKv7, GAUv6 and GAUv7) with the rain-gauge dataset (OBS) for daily (a1, a2, a3) and 6-hourly accumulated rainfall (b1, b2, b3).

MVKv7 seemed to be sensitive to delta plains or river basins since it again showed higher estimation in the Southern Plain region (S3), whereas GAUv6 and GAUv7 showed notable negative values for the western stations.

Although it was difficult to distinguish the ME maps of GAUv6 and GAUv7, their difference still appeared at several stations, chiefly at coastal stations and islands. For example, in the regions located around 16.3°－18°N, the Bach Long Vy station (20.13°N–107.72°E), and the Con Dao station (8.28°N–106.6°E), GAUv6 typically had higher precipitation estimation but GAUv7 tended to considerably underestimate precipitation. This raised a concern for the development of the weak rain detection algorithm of GSMaP version 7 because it was assumed that by taking the cloud liquid water into account, the rainfall over the ocean could be improved in GSMaP v7. Owing to the limitation of direct rainfall measurement over the ocean, it should be carefully considered whether the rainfall estimation above islands can well represent the effectiveness of the methodology used.

The RMSE results in Fig. 3 once again confirm the larger differences of MVKv7, with the RMSE values of most stations being closer to pink than to yellow part of the color scale in GAUv6 and GAUv7. While a mixture of the highest and the smallest RMSE values could be seen in northern Vietnam, certainly high RMSE values were observed in the southern coastal region (S1), clearly in the 6-hourly rainfall estimation of the three products. Considering the rainfall ratio values between daily and 6-hourly datasets, the fact that the 6-hourly maps presented surpassing color scales than the daily maps implied a larger variation in the errors of the 6-hourly temporal resolution than in those of the daily temporal resolution. Hence, the utilization of short-range rainfall datasets, such as flood or thunderstorm warnings, should take those issues into consideration in order to obtain precise results.

To sum up, first declaring about the performance of GSMaP standard and the standard with gauge calibration, the comparison between MVKv7 and GAUv7 suggested the outer performance of standard with gauge-calibrating products for most regions over Vietnam except the Highland region where MVKv7 tended to present more homogeneously than GAUv7. However, the MVKv7 product significantly overestimated precipitation over the Northern Delta, the coastal part of the Northeast region, and the Southern Plain. Places with complicated topographic features or transitional climate like northern mountainous areas and central coastal regions, remain difficult subjects for satellite rainfall estimation according to the aforementioned findings. The improvement could be achieved by adding more stations when adjusting standard products because the modulus of mean errors at GAUv7 was modest than that of MVKv7 at some stations. The second conclusion about the upgrade version compared with its prior product is that there was a little difference in the performance of GAUv6 and GAUv7, while considering the overall ME and RMSE indices. The discrepancies only emerged at a small scale of stations or regions, such as central coastal areas and islands. The improvement in the upgraded version should be more clearly investigated by considering other conditions and aspects. The relative uniformity of the ME maps between daily and 6-hourly data of all three products revealed less difference in accumulated rainfall estimation for 6 h and one day; however, the RMSE analysis suggested that the variation of errors in the shorter temporal resolution was larger than that in the daily sample.

Linkage between rainfall assessment and elevation

Previous studies have mentioned that satellite rainfall estimation was quite poor in high-altitude areas because of its ability to detect warm orographic rainfall (Dinku *et al*. 2007; Ngo-Duc *et al.* 2013; Trinh-Tuan *et al.* 2019). These studies were performed for GSMaP reanalysis version 5 and version 6. As specified above, although a slow convective detection method was improved in the latest version, MVKv7 and GAUv7 still had difficulties in estimating rainfall at mountainous areas and complex places, or even worse than GAUv6 for some stations in Vietnam. Thus, the scatter plots between the ME with the elevation of the stations associated with their linear relationships demonstrated this analysis for daily and 6-hourly resolutions in Fig. 4. It should be noted that the N1, N2, N4, and S2 regions generally process higher elevations than the N3, S1, and S3.

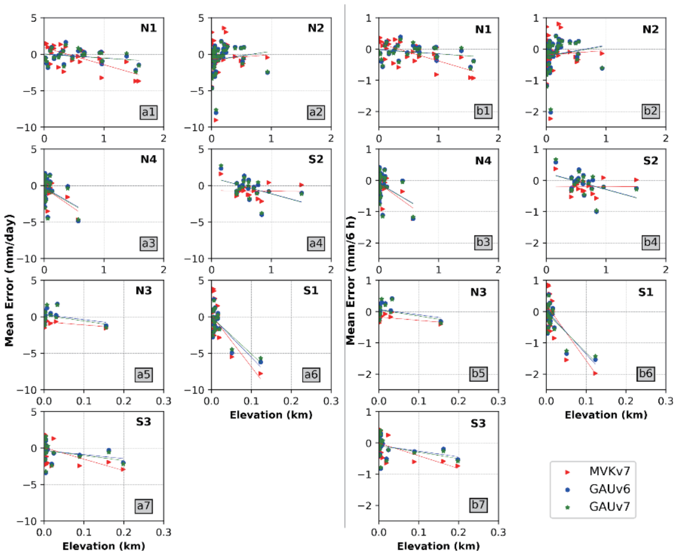

Fig. 4 Scatter plots of mean error and elevation for all stations at seven sub-climate regions for (from a1 to a7) the daily and (from b1 to b7) 6-hourly dataset. The linear relationship of each satellite rainfall estimation product (MVKv7, GAUv6, GAUv7) with elevation is also displayed.

In the group of high-altitude stations, the relationship between satellite rainfall estimation and elevation was quite common in the N1 and N4 regions, while in N2 and S2, a contrasting trend was observed. The inverse ratios presented in N1 and N4 suggested that rainfall estimation would bring more biases in lower-altitude stations. This pattern can be clearly seen in the N4 and S1 regions. These findings are consistent with the results of Ngo-Duc *et al.* (2013), who reported that the differences between GSMaP and rain-gauge observation increased more largely in downstream basins than in upstream regions. Whereas, though the height of mountain ranges within N2 are less than those in the N1 region, the complexity of topography could be the reason for the proportional linear regression of satellite rainfall estimations. This requires a further analysis to explain the overestimation of MVKv7 for the coastal region and the underestimation of three products for stations having lower elevations between mountain ranges.

Differences based on rainfall thresholds

The ability of GSMaP to detect a wide range of rainfall is presented as the box plot in Fig. 5. It is clear that the higher the number of datasets, the larger is the STDN. To be specified, three GSMaP products presented high STDN at a threshold (<0.6 mm/day or <0.15 mm/6 h) that could be considered as no-rain classification while the ratio of STDN at the highest rainfall amount (corresponding to extremely heavy rainfall) received the smallest values. This suggests a high potential of GSMaP product for detecting heavy rain cases.

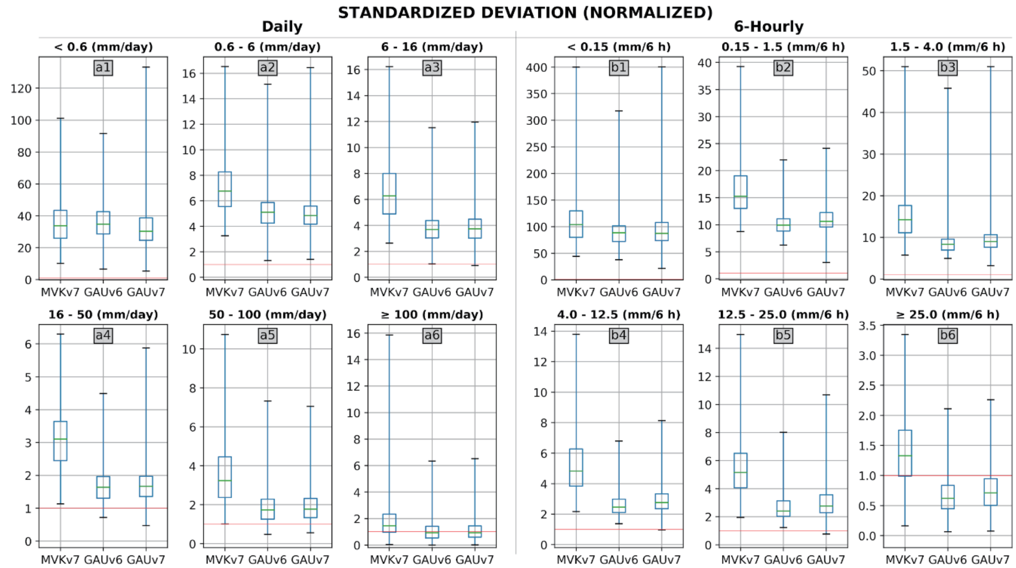

Fig. 5 Normalized standard deviation of satellite rainfall estimation data (including MVKv7, GAUv6, GAUVv7) and rain-gauge dataset which was daily accumulated rainfall (a1, a2, a3, a4, a5, and a6) and 6-hourly accumulated rainfall (b1, b2, b3, b4, b5, and b6) based on 6 rainfall thresholds. The red line presents the ratio value equal 1, corresponding to the best performance of satellite estimation.

Among the three products, MVKv7 always had the highest median; GAUv7 showed the smallest range between the upper and lower fences. Daily GAUv7 product showed the "closest to 1" median compared to the other products with the same temporal resolution, whereas the

6-hourly GAUv6 tended to be the best, excluding the threshold of (≥25 mm/6 h). Overall, the performance of GAUv7 was better than that of MVKv7 for moderate to extremely heavy rainfall, while the latter product showed its more homogeneity for thresholds below 6 mm/day (1.5 mm/6 h). The argument about rainfall estimation in GAUv6 and GAUv7 continued when analyzing threshold conditions. For the daily dataset, GAUv7 showed a better performance, opposite to that in the 6-hourly dataset. However, at both temporal resolutions, the larger distance between the two fences of GAUv7 evoked the upgrading methodology in GSMaP version 7 unequally for all stations.

4. Conclusions

The performances of three GSMaP products (MVKv7, GAUv6, and GAUv7) were analyzed based on two temporal timescales with considering the relationship between satellite rainfall estimation and elevation as well as rainfall thresholds. In terms of spatial performance, despite of possessing the same latency with respect to the observation, owing to the difference in detecting and estimating algorithms, a large contrast could be seen between MVKv7 and the group of GAUv6 and GAUv7, in which the standard with gauge-calibrating products seemed to perform better for most regions except the Highland region of Vietnam, wherein MVKv7 overestimated largely in the Northern Delta, partly in the Northern Central and the Southern Plain. This suggests a better quality of GSMaP standard product for the Highland region and standard with gauge-calibrating product for the remaining areas when considering using GSMaP for multiple purposes. However, all three products still showed poor performance over the mountainous areas and the transitional-climate regions, such as the northernmost places and the regions located at approximately 16.3°－18°N, and around 12°N. According to the rainfall threshold analysis, GSMaP presented potentially a good capture of heavy rainfall (over 50 mm/day), while according to the lower classification (<6 mm/day), satellite rainfall estimation showed more variation, being more homogeneous in MVKv7 than GAUv7. The results obtained from linear regression between ME and elevation again confirmed that the biases of GSMaP were higher in the downstream basins of most regions than in places with higher elevation, especially in the N4 and S1 regions. Nonetheless, the discrepancies between GAUv6 and GAUv7 were not clear. Though the median of the box belonged to GAUv7 tended to be closer to the best value than those of GAUv6, the wider range between the upper and lower fence suggested the broader variations of GAUv7. Besides, the shorter time resolution, the higher error amplitudes presented when comparing the performance of the daily and 6-hourly accumulated GSMaP rainfall dataset. Therefore, the further study will clarify complex patterns of biases in sub-climate regions in Vietnam, as well as controversial performances of gauge-calibrated products.

Acknowledgments

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