Spatial Rainfall Rate Estimation from Multi-Source Data in Klang Valley, Malaysia

Asmat, A.,[1,2*] Hazali, N. A.,[1] Sahak, N.,[1] Tahir, W.[3] and Ramli, S.[3]
[1]School of Chemistry and Environment, Faculty of Applied Sciences, Universiti Teknologi MARA (UiTM), 40450 Shah Alam Selangor, Malaysia, E-mail: rnis_annis@uitm.edu.my, atiqahazali92@gmail.com, nurainshafikasahak06@gmail.com
[2]Climate Change & Carbon Footprint Research Group, Universiti Teknologi MARA (UiTM), 40450, Shah Alam, Selangor, Malaysia, E-mail: rnis_annis@uitm.edu.my
[3]Faculty of Civil Engineering, Universiti Teknologi Mara (UiTM), 40450 Shah Alam Selangor, Malaysia E-mail: warda053@uitm.edu.my, suzana799@uitm.edu.my
Correspondence Author

Abstract
This study investigates rainfall distribution by estimating rainfall rate from multi-source data of rain gauge, radar image and TRMM in Klang Valley, Malaysia. The study is also looking into rainfall intensity to identify rainfall types based on 35mm/hr thresholds for 5-minute interval using ground rain gauge data measurement. The results revealed that during the study period, the stratiform rainfall type was found dominant, and most of the rainfall events occurred during the evening. The simple regression and bias error analysis have conducted to assess the potential of radar image and TRMM for rainfall estimation rate. It has shown a positive but relatively weak relationship of regression coefficient between the rain gauge measurements and both data sources. The results indicated that radar image has better performance than TRMM satellite in rainfall rate estimation over Klang Valley. The radar has estimated a total rainfall rate of about 42.5mm/hour with percent bias are (-14.49%) of error relative to rain gauge data measurement. Meanwhile, the per cent bias for TRMM tends to underestimate the rainfall measurement by (-42.05%) with only 28.8mm/hour total rainfall rate were estimated. The spatial interpolation of the IDW technique reveals the rainfall distribution pattern in the study area, interpolated rainfall distribution from a radar image has shown a good agreement with rainfall distribution from rain gauge data measurement. Although radar image has higher accuracy in rainfall rate, estimation due to limited data availability used in this study was unable to reveal the rainfall pattern. Furthermore, both data products used in this study show a lower ability to detect high-intensity rainfall events due to limited data availability appropriately.

1. Introduction

Over the past two decades, a large number of rainfall products have been developed on satellite-based, radar-based and rain gauge observations (Kumar et al., 2020 and Kidd and Huffman, 2011). However, the uncertainties of rainfall variability due to the space-time variability of rainfall at many scales and the spatial and temporal sampling hampered the optimal rainfall estimation data (Long et al., 2016). In addition to ground measurement, the used radar-based and satellite-based rainfall products have become immensely important since ground observation locations are scattered sparsely (Hur et al., 2016).

In Malaysia, flash flood events often occur in urban areas such as the Klang Valley, where the significant factors that have influenced the flood formation are its variability in time and space (Kidd and Huffman, 2011 and Akbari et al., 2011). Damages and losses caused by flash floods are increased over the years (D/iya et al., 2014). The storms of convective origin by a sudden burst of heavy rainfall over a short period are generally known to be responsible for much of flash flood events in urban areas (Syafrina et al., 2015). Despite the strong association between rainfall pattern and major flash flood, the linkages have not yet to be sufficiently established (Nandargi and Mulye, 2012). The main reason is the difficulty in getting reliable convective rain data, which has not readily identified in meteorological records. Besides, the rainfall pattern also can be affected by many factors like topography (Wong et al., 2016 and Huang et al., 2015), temperature (Huang et al., 2015), wind (Wong et al., 2016) and seasonal and transition monsoon (Bharti and Singh, 2015 and Fadzilatulhusni et al., 2011).

Conventionally, rainfall data is collected at discrete point locations over space at rain gauges meteorological stations (Muller, 2011) and limited in their spatial coverage (Yang and Luo, 2014 and Wetchayont et al., 2013). In a small area, obtaining accurate rainfall information is a considerable challenge, and this has influenced temporally and spatially variation of rainfall (Hur et al., 2016). Data acquired from rain gauges often have missing rainfall data in the observation or insufficient rainfall stations (Wong et al., 2016). Errors of sparsely located (Yang and Luo, 2014) can arise using point rain gauges to represent rainfall in radar or satellite pixels (Wetchayont et al., 2013).

The remote sensing technology offers high temporal and spatial resolution (Wetchayont et al., 2013) and has excellent coverage over mountainous areas (Yang and Luo, 2014). However, there are still some limits due to inter-radar calibration and radar beam blockages by topography (Wetchayont et al., 2013). Meanwhile, satellite TRMM has provided accurate global tropical precipitation estimates (Su et al., 2008) and accurately detected precipitation occurrences on a daily scale. Despite this limitation, both data mentioned are produced better space-time distribution of precipitation and has consistency with rain gauge observations (Bharti and Singh, 2015 and Yang and Luo, 2014). The drawback from TRMM estimates is due to the temporal and spatial scale, which lead to uncertainties in estimating rainfall at the small-scale region (Mahmud et al., 2015); besides, the TRMM precipitation algorithm also poor sensitivity to low and high precipitation clouds (Varikoden et al., 2010). The effect of upscaling the rainfall rate to a practical temporal scale (Prasetia et al., 2013) and the coarse grid size of the TRMM data for solving local rainfall patterns (Zad et al., 2018) also hampered the accuracy of the estimation. Therefore, it is essential to investigate rainfall distribution by estimating rainfall rate from multi-source data of rain gauge, radar image and TRMM in Klang Valley, Malaysia. Typically, rainfall rate measurement based on rainfall intensity by calculating the amount of rainfall in a given time interval and expressing length (depth) per unit time. The study is also looking into rainfall intensity to identify rainfall types based on 35mm/hr thresholds for 5-minute interval using ground rain gauge data measurement.

2. Data and Method

The study's location is in Klang Valley, Malaysia is delineated by the Titiwangsa Range to the northwest, Semenyih in the southeast and Port Klang in the Southwest and receives yearly rainfall of about 2946.8mm. In Malaysia, the Northeast monsoon and Southwest monsoon are two significant monsoons that blow a wet season from October to March and h blows a dry season from June to September (Zad et al., 2018 and Fadhilah et al., 2007). Geographically, the study site is situated in the hub of one of the busiest areas in Malaysia between Selangor and Kuala Lumpur. This area is also pressing from its rapid urbanization and a high population (Al Mamun et al., 2018; Varikoden et al., 2011). The area susceptibility to flash-flood prone due to the high occurrence of convectional rainfalls and large areas of the impervious surface (Varikoden et al., 2011), especially during April to May and October inter-monsoon occurred (Lung, 2016). These two shorter periods of inter-monsoon seasons are marked by heavy rainfall as it yields uniform periodic changes in the wind flow patterns over the study site (Mohd Akhir et al., 2014).

The rain gauge rainfall data are obtained from the Department of Irrigation and Drainage (DID) Selangor. One year of rainfall data between March 2007-April 2008 at eighteen stations in Klang Valley was used for rainfall types classification using 5-minutes interval rainfall intensity. The threshold with less than 35mm/hr categorizes as a stratiform rainfall type. Meanwhile, convective rainfall should occur more than 35mm/hr (Ahmad et al., 2008). Satellite estimate of TRMM 3B42RT version 7 datasets were obtained from https://pmm.nasa.gov/data-access/downloads/trmm product 3B42RT version 7 with a 3-hours temporal resolution and 0.25◦ × 0.25◦ approximately 27.8 km × 27.8 km spatial resolution (Varikoden et al., 2011). The data extracted for the region covering Klang Valley was dated on the 29th February 2008 and 1st March 2008 using GIS 10.9. To ensure all the data used in this study were temporally closed to each other, the TRMM rainfall values were retrieved by cells within an average of three hours before and three hours after the event, which was similar approached used by (Akbari et al., 2011).

Meanwhile, as for radar image, only available on the 1st March 2008 was obtained from Malaysia Meteorological Department (MMD). Radar reflectivity data was obtained from S-band Terminal Doppler Radar in KLIA, operated by MMD (Malaysia Meteorological Department) and located at an elevation of 37 m MSL. The conventional radar data are collected every 10 minutes up to the effective range of 230 km for three elevation scans (PPI) with elevation angles of 1.0°, 2.0° and 3.0° (Ramli and Tahir, 2011). Later, the rainfall values are retrieved from a radar image using a digitizing process in ArcGIS 10.9.

The differences between estimated rainfall values were derived using percent of error (PE) relative bias (Bharti and Singh, 2015 and Akbari et al., 2011) as follows:

$$\text{Relative Bias} = \frac{\Sigma\,(Ei - Oi)}{\Sigma Oi} \times 100$$

Equation 1

Ei estimates the imaging data, and Oi is the observation from the rain gauge data. The spatial interpolation techniques are a reliable approach to estimate climate information for unobserved locations from nearby measurements (Berndt and Haberlandt, 2018).This approach resolves such partial rainfall data; probable rainfall data can be estimated using the technique (Chen and Liu, 2012). In this study, to observe rainfall distributions, an Inverse Distance Weighting (IDW) was applied on rain gauge, radar and TRMM (Waken et al., 2018). The drawback with this technique is that it assumes that maximum and minimum values are measured at the sampled points, and all other unsampled points have values between those values (Grimpylakos et al., 2013).

3. Results and Discussion

In Figure 1, a plot of one-year rainfall data from rain gauge data measurement. The results show about 68% of the total rainfall has occurred during a daytime period at 0700h until late evening at 1900h as compared to 32% of total rainfall recorded after 1900h and onwards. Besides, the highest amount of rainfall was recorded at about 542.2mm at 1700h. It shows the pattern of rainfall events in the afternoon at 1400h until it has reached the highest peak in the late afternoon at 1700h. A similar study by (Varikoden et al., 2011) also found that the rise of rain occurrences observed at 1700h. High rainfall events in the late afternoon and late evening may happen due to warm moist air by diurnal heating associated with the strong solar irradiance at low latitudes (Wu et al., 2009). Figure 2 shows the highest rainfall rate has been recorded in June, about 495mm, and in April, with a total amount of rainfall has recorded about 475.2mm.

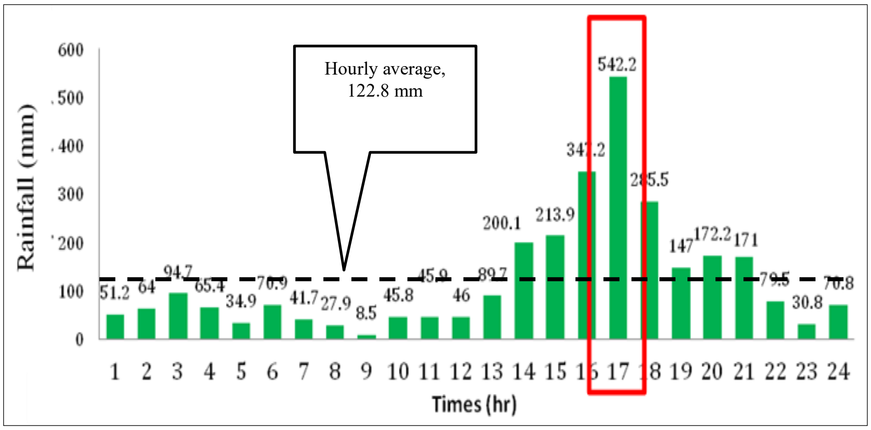

Figure 1: Rainfall amount in mm with the 24-hours measurement for April 2007 until March 2008. Diurnal rainfall shows the rain falls starts in the afternoon at 14:00hr and reach its highest peak at the 17:00hr

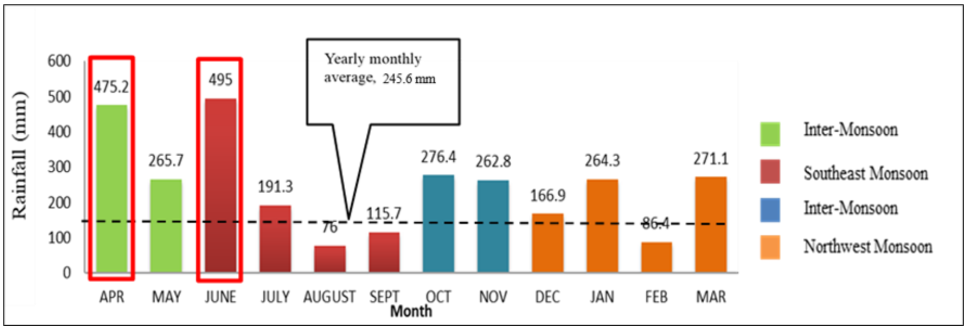

Figure 2: The monthly amount of rainfall during four dominants seasonal in April 2007 until March 2018. The graph shows that the rainfall intensity exceeded the yearly monthly average (245.6mm) for most of the months regardless of specific monsoon

Many studies have found a similar trend of extreme rainfall in Peninsular Malaysia, which occurs during April-May throughout the year (Syafrina et al., 2015). As stated by (Zad et al., 2018 and Mohd Akhir et al., 2014), these two inter-monsoon seasons typically happened in a short period with uniform periodic changes in low wind pattern has yielded heavy rainfall. The magnitude of rainfall during inter-monsoon can also enter the other season (Al Mamun et al., 2018). Climate change has been one reason for the distribution and rainfall rate (Kidd and Huffman, 2011). This scenario can be observed on total rainfall in June, which falls during the Southeast Monsoon and has recorded about 495mm. Furthermore, a study by (Syafrina et al., 2015) has revealed the extreme rainfall events patterns from 1975-2010 in Peninsular Malaysia normally occurs during April-May. They also found the rainfall amount during these periods can be up to 49.93mm to 491.87mm.

As the study area is located in a tropical country, the convective rainfall types are expected to be dominant (Ahmad et al., 2008), which is not the case during the study period. Several factors may contribute to the finding, one of the significant caused are limited data availability (Huang et al., 2015), underestimated ground measurement data due to the effect of wind at the mouth of the rain gauge, wetting, evaporation, splashing, and the inadequate spatial coverage of rain gauge stations and magnitude of the error (Wong et al., 2016 and Varikoden et al., 2011). Also, rainfall trend is not only affected by weather and climate, but sparsely location of the station, topographic location of station and data measurement instrument will also influence the homogeneity of rainfall time series (Waken et al., 2018).

The estimated rainfall rate from a rain gauge, radar image and TRMM is tabulated in Table 1. The results show the total rainfall rate was measured from the rain gauge measurement of about 49.7 mm. Radar image has produced a slight difference with the total estimated rainfall rate of 42.5mm. Meanwhile, the estimated total rainfall rate from TRMM was too low, with only recorded about 28.8mm. Overall results from all stations; showed discrepancies of rainfall rate estimated between rain gauge and both data sources: radar and TRMM. Inconsistent rainfall estimation was showed at station R14 and station R15, where radar has recorded high rainfall rate values and TRMM has recorded low rainfall rate compared to rainfall measured from the rain gauge. Similar results can be found from (Ahmad et al., 2008) where substantial differences of value were found between radar and rain gauge measurement. The evaporation process of precipitation can cause a different reading between rainfall and radar before reaching the ground, which may be more intense in the tropic region (Bharti and Singh, 2015; Yu et al., 2014).

Table 1: The estimated rainfall rate in (mm/hr) from rain gauge measurement, radar and TRMM on the 1st March 2008

No.	**Stations**	**Ground Observation**	**Radar Image**	**TRMM**
		Rainfall Rate (mm/hr)		
R1	3116006 - Ldg Edinburgh Site 2	2.0	0.8	2.19
R2	3217003 - KM11 Gombak	1.0	1.0	1.57
R3	3216001 - Kg Sg Tua	5.0	0.5	1.17
R4	3116003 - JPS Malaysia	3.5	0.4	2.42
R5	3018101 - Emp. Semenyih	0	0	1.83
R6	3118102 - SK Kg Lui	0	0	1.85
R7	3119104 - Jln Genting Peres	0	0	2.05
R8	2917001 - JPS Kajang	0	0	1.37
R9	3117070 - JPS Ampang	0	0.6	2.21
R10	3115079 - Pusat Penyelidikan Sg Buloh	10.0	10.0	2.44
R11	3315037 - Tmn Bkt Rawang	3.0	1.1	1.02
R12	3315038 - Country Home	2.1	1.1	1.77
R13	3217004 - Kg Kuala Sleh	3.0	0	1.35
R14	3217002 - Emp. Genting Klang	4.1	13.0	1.54
R15	3317001 - Air Terjun Sg Batu	5.0	12.0	0.57
R16	3317004 - Genting Sempah	6.0	2.0	0.41
R17	3014091 - UiTM Shah Alam	3.0	0	1.32
R18	3014084 - JPS Klang	2.0	0	1.72
	TOTAL	**49.7**	**42.5**	**28.8**

The wind movement can also be affected (Wong et al., 2016) when the winds are carried away by precipitation from beneath the rain-producing cloud. The discontinuities in the vertical distribution of rainfall in the cloud may also affect the reflectivity and other errors (Kumar et al., 2020).

The regression coefficient generally shows a positive but weak relationship between the rain gauge measurements and both data sources of radar and TRMM with R2 (0.3792) and R2 (0.0374), respectively. The results in Table 2 has indicated that radar image has better performance than TRMM satellite in rainfall rate estimation over the Klang Valley region. The estimated total rainfall rate from the radar is about 42.5mm/hour with percentage bias are (-14.49%) of error relative to rain gauge data measurement. Meanwhile, the percent bias shows that TRMM tends to underestimate the rainfall measurement by (-42.05%) with only 28.8mm/hour rainfall rate were estimated. Overall, rainfall estimated from radar was slightly underestimated with rain gauge measurement, and similar finding has been found by (Muller, 2011). Several factors may influence the negative bias, i.e., altitude (Yu et al., 2014), where radar rainfall intensity observes almost instantaneously at the volume of the atmosphere with 1km^2 surface projection, while rain gauge accumulates continuous rain falling on the area smaller than 1m^2 (Muller, 2011). The negative bias has indicated that the rainfall rate estimated from radar and TRMM is less than from rain gauge data measurement and *vice-versa* for positive bias (Akbari et al., 2011). A study by (Hur et al., 2016) also found underestimated rainfall rate on satellite-based estimation. Several reasons have made intrinsically different between satellite-based measurement and ground observation. The satellite's rainfall measurement is based on the average value within a pixel due to its field-of-view and point value from ground measurement (Zad et al., 2018).

The spatial distributions of rainfall were derived by inverse distance weighting (IDW) on rain gauge, radar and TRMM. The interpolated rainfall distributions from the radar image have shown good agreement with rainfall distribution from rain gauge data measurement, as shown in Figure 3a-3c**.** The rainfall contour patterns of radar data have exhibited similar patterns with rain gauge data measurement. However, rainfall distribution from TRMM failed to show good agreements between radar and rain gauge data. Overall, the isohyetal lines derived from the rain gauge, radar and TRMM data are smoothly produced by IDW. Moreover, the spatial distributions between TRMM and radar rainfall are remarkably different, especially at a low rainfall rate.

Table 2: The percent error (PE) % derived from estimated rainfall rate from radar and TRMM on the 1st March 2008

No	**Station**	**Ground (mm)**	**Radar Image (mm)**	**PE %**	**TRMM (mm)**	**PE %**
R1	3116006 - Ldg Edinburgh Site 2	2	0.8	-2.41	2.19	0.38
R2	3217003 - KM11 Gombak	1	1	0.00	1.57	1.15
R3	3216001 - Kg Sg Tua	5	0.5	-9.05	1.17	-7.71
R4	3116003 - JPS Malaysia	3.5	0.4	-6.24	2.42	-2.17
R5	3018101 - Emp. Semenyih	0	0	0.00	1.83	3.68
R6	3118102 - SK Kg Lui	0	0	0.00	1.85	3.72
R7	3119104 - Jln Genting Peres	0	0	0.00	2.05	4.12
R8	2917001 - JPS Kajang	0	0	0.00	1.37	2.76
R9	3117070 - JPS Ampang	0	0.6	1.21	2.21	4.45
R10	3115079 - Pusat Penyelidikan Sg. Buloh	10	10	0.00	2.44	-15.21
R11	3315037 - Tmn Bkt Rawang	3	1.1	-3.82	1.02	-3.98
R12	3315038 - Country Home	2.1	1.1	-2.01	1.77	-0.66
R13	3217004 - Kg Kuala Sleh	3	0	-6.04	1.35	-3.32
R14	3217002 - Emp. Genting Klang	4.1	13	17.91	1.54	-5.15
R15	3317001 - Air Terjun Sg Batu	5	12	14.08	0.57	-8.91
R16	3317004 - Genting Sempah	6	2	-8.05	0.41	-11.25
R17	3014091 - UiTM Shah Alam	3	0	-6.04	1.32	-3.38
R18	3014084 - JPS Klang	2	0	-4.02	1.72	-0.56
	TOTAL	**49.7**	**42.5**		**28.8**	
			Relative Bias	**-14.49**	**Relative Bias**	**-42.05**

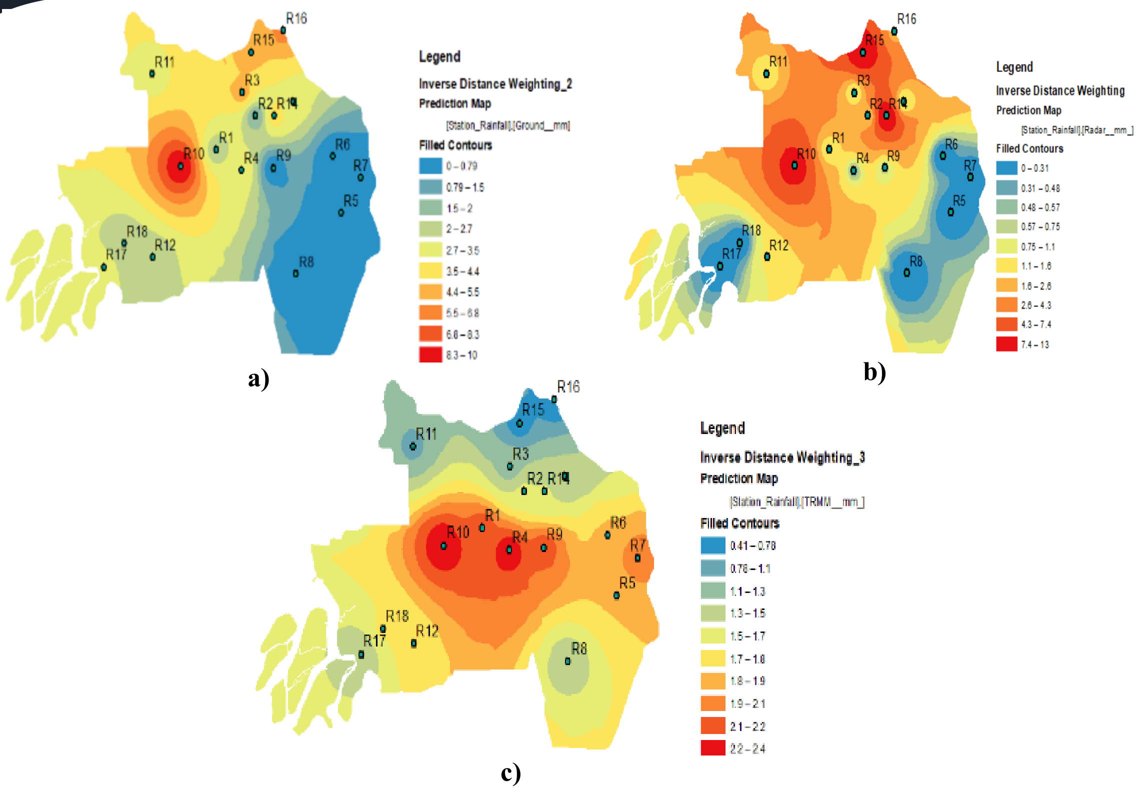

Figure 3: Rainfall distribution pattern on the 1st March 2018 using an Interpolation Distance Weighted (IDW) for a) ground observation b) Radar and c) TRMM

This happened might be due to the uncertainties of TRMM (Mahmud et al., 2015 and Chokngamwong and Chiu, 2008) and further complicated by is the occurrence of missing data for some of the events.

4. Conclusion

This study explored the potential of estimating the rainfall from multi-source data of rain gauge, radar and TRMM for rainfall estimation rate in Klang Valley, Malaysia. However, estimating rainfall from high spatiotemporal rainfall fields is challenging when only a sparse rain gauge network and coarse spatial resolution of satellite data are available. The results of this investigation showed that the radar and TRMM products used in this study offer a lower ability to detect high-intensity rainfall events appropriately. Regardless of the limitation, yet radar has performed better in estimating rainfall rate than TRMM data in the study areas. Since satellite-based rainfall products are estimates from indirect measures (e.g., IR cloud-top temperature), they are prone to errors greater than radar-based rainfall measurements. Many studies reported that the temporal and spatial scale is crucial in affecting the performance for both data radar and TRMM rainfall estimates, especially for local-scale rainfall in a small region. Also, the uncertainties include the availability of the TRMM precipitation algorithm to be more sensitive to low and high precipitation clouds, the effect of upscaling the rainfall rate to a practical temporal scale, and the coarse grid size of the TRMM data hold back in solving local rainfall patterns.

Moreover, the 'non-representative sampling' error has also limited radar's ability to detect small particles, which occurs predominantly during weak rainfall events. Since rainfall significantly varies over distance and change during the time interval, it seems the gauge measurement may not entirely represent the area sampled by radar. It is suggested that the 'non-representative sampling' error could be reduced by interpolating rain gauge values (before analysis) into a grid (mean areal precipitation) matching the size of radar's pixels.

The point-based observations of rainfall provided by rain gauges are not always dense enough to accurately represent a region's rainfall, as presented in this study. Hence, smaller sampling, and random errors can arise in using point rain gauges to represent rainfall of a radar or satellite pixel, particularly in areas where the rain gauge network is relatively sparse. In contrast, it has been found that radar provides pixel-based area rainfall measurements with better spatial coverage that is more comparable to the scale of satellite imagery. This encourages the use of high-resolution rainfall product, which can be obtained from combined satellite-based estimates with radar-based. To improve the accuracy, the bias of any of the products relative to each other should be removed. In the absence of ground-based radar data over the study, the region makes the evaluation methods rely solely on rain gauges; therefore, the validation approaches are limited. On the other hand, more data for radar and TRMM measurement are critically needed to improve the accuracy of existing work and provide better insight into the study area's rainfall rate pattern.

Besides, understanding rainfall estimates at a finer scale over the study site, cloud formation, classification, and characteristics are essential in precipitation. Each of these factors should be analyzed to get more accurate results in rainfall estimation. In this study, rainfall is based only on the clouds' top temperature, ignoring their characteristics. The type of precipitation (convective or stratiform) will determine the rainfall rate, whereas identifying the precipitation type using remote sensing techniques is still a challenge. TRMM shows a weak to moderate performance at the daily scale which is better suited to estimate monthly cumulative rainfall than shorter time ranges.

Similarly, radar estimated rain rates observed instantaneously at any given measurement cell may not represent intensities during the intervals between observations. Also, limitation in the existing rainfall estimation method that provides radar rainfall on average instead of the actual rainfall may result in underestimated rain by radar. Nevertheless, these deficiencies could be refined by improving rainfall retrieval by distinguishing between convective and stratiform clouds where the precipitation growth in both conditions is different.

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