SPATIO-TEMPORAL ASSESSMENT OF MONTHLY GPM AND TRMM: A PRELIMINARY STUDY IN COASTAL AND INLAND AT SABAH AND SARAWAK, MALAYSIA

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ABSTRACT: Although the IMERG Global Precipitation Measurement (GPM) and Tropical Rainfall Measurement Mission (TRMM) are involved in providing data in the tropic at regional scale, it is necessary to evaluate their performance since coastal and inland areas have different rainfall distribution patterns in terms of spatial and temporal variations. Despite continued overall good performance of TRMM, the mission was decommissioned in 2015 and was replaced by GPM from 2014 onwards, with an expectation that the later will provide better products for various applications including land hydrology, coastal, and nearshore areas. This study aims to evaluate the monthly capability of GPM during the overlapped period of TRMM-GPM together (March 2014-March 2015), by using the product of Final Run Monthly (GPM) and 3B43 V7 (TRMM) with 13 rain gauges (7 coastal and 6 inlands) over Borneo Island (Sabah and Sarawak). The evaluations were conducted by dividing the area into two spatial categories: coastal and inland. Five statistical evaluation tools were used: bias (B), mean absolute error (MAE), root mean square error (RMSE), absolute percentage error (APB), and Nash-Sutcliffe (N*r*). The result indicates that: (1) the error of spatially assigned spatial category varied consistently for GPM and TRMM (Δb= 0.206, -32.591; ΔMAE=-18.107, -29.044; ΔRMSE=-11.288,-23.073; ΔAPB=-5.569, -10.140; ΔN*r*=0.188; 0.273) respectively to the aforementioned satellite types; (2) overall temporal error existed on all months with pattern were subjected to the monsoon characteristics with spatial categories persisted affecting both satellite precipitation altogether (b=-105–55mm; MAE=117–18mm; RMSE=23–157mm; APB=9–23mm and N*r*=-0.149–0.98). Notably, 70% out of the 48 months for inland-coastal are in good agreement in N*r* indicator. Such finding suggests value added for understanding of the new generation of satellite precipitation (GPM) towards spatio-temporal characteristics especially on inland-coastal relationship. Acceptable tolerance of accuracy shows better GPM usability of the monthly product in sustainable field.

Keywords: coastal-inland satellite precipitation, spatio-temporal variations, monthly GPM-TRMM error assessment, Borneo island, Sabah and Sarawak.

1.0 INTRODUCTION

Precipitation, particularly rainfall, is one of the important variables in the hydrological cycle and their behaviour are dynamic in temporal and spatial. Moreover, they play a major role in the weathering process as one of the elements that change the earth landscape (Jaafar *et al.*, 2011). Thus, it is important to obtain space-time rainfall information for further applications. However, monitoring rainfall have been challenging when using observation networks where they are limited to station availability and coverage (Fensterseifer, 2013; Huffman *et al.*, 1995). Despite advancement rain gauge network, they are subjected to data availability (Villarini *et al.*, 2008) and the owner of the systems where data sharing and national security reduce the global spatial representation of the rainfall pattern (Kroese, 2004). Provided with this condition, scarce constant data availability between different landscapes such as in land and coastal create low reliability in retrieving more information from rainfall pattern interpretation.

In the past years, remote sensing satellite was launched in attempt to collect precipitation information (Bytheway & Kummerow, 2013; Turk & Miller, 2005). Initially, the satellite monitoring was done using a platform such as the Tropical Rainfall Measurement Mission (TRMM) and the coverage was limited within latitude 50°N to 50°S, temporal of 3-hour as well as spatial of 0.25°. However, satellite orbiting the earth have limited lifespan depending on spacecraft system stability such as fuel availability and sensor capability. Consequently, the TRMM which operates from 1998 to 2015 was decommissioned (2015) and replaced by Global Precipitation Measurement (GPM) from 2014 onwards, with better sensor, wider coverage (65°N to 65°S), higher spatial resolution (0.1°), higher temporal resolution (30 minutes) and more platform by including unify satellite constellation other than GPM core observatory

(Huffman *et al.*, 2014). With more scientific instrument and better mission planning, GPM is expected to provide better products for various applications including land hydrology, coastal, and near shore areas.

Various satellite precipitation validations were done throughout the world (Hossain & Huffman, 2008; Silva Lelis *et al.*, 2018; Tan *et al.*, 2016). On the other hand in the study carried out in Mexico depicts that the GPM is affected by topography structure (Mayor *et al.*, 2017). As in Asia, specifically in Korea, Kim *et al.* (2017) found uncertainties for both of the satellites affected by the orographic convection, while GPM performed better in the analysis of straight cross section from coastal to land. In India, Chanyatham and Kirtsaeng (2011) found bias existed on the hilly area and high rate rainfall. Within the study area of Singapore, Tan and Duan (2017) assessed the GPM and TRMM product resulted in slight improvement in GPM accuracy. Meanwhile, study done in Malaysia (Tan & Santo, 2018) which assessed both satellites together with PERSIAN-CDR, they discovered that GPM has better sensitivity in detecting rainfall. Other assessments on TRMM in West Malaysia conducted by Nadzri and Hashim (2013) have shown improvised accuracy when comparing the version 6 and 7 side by side. All conducted studies compared the satellite performance as well as accuracy.

Nevertheless, although the aforementioned studies included topography and orography effect in the local based analysis, in depth study on inland and coastal variation have not been executed in tropic nor reported together. Therefore, this study was carried out to assess the monthly capability of GPM during the overlapped period of TRMM-GPM together (March 2014-March 2015), by using the product of Final Run Monthly (GPM) and 3B43 V7 (TRMM) in coastal and inland.

2.0 MATERIALS AND METHODS

2.1 Study Area: The study was conducted within the South East Asia portrayed through the red box in Figure 1, where Sarawak state is labelled as A while Sabah as B. The landmass is located in the Borneo Island. It is surrounded by sea in the west (South China Sea), and north east (Sulu Sea), while it is occupied mostly by hilly areas bordering the two nations of Malaysia and Indonesia in the south. Specifically, the study area is situated in the latitude/longitude of 109°-119°E and 0°-7°N respectively.

Since the location is in tropical region, the study area experiences mix of bright sunlight and high frequency of rainfall throughout the year. This region also experiences two distinct monsoon and inter-monsoon seasons. The monsoons are North East Monsoon (NEM) starting from November to March, and South West Monsoon (SWM) that occurs from May to September. Other monsoon types are namely warm (dry) inter-monsoon, which occurs from December to February and June to July; while humid (wet) inter-monsoon occurring in April to May and September to November. It was previously recorded that heavy rainfall can accumulate up to 2500mm in the area.

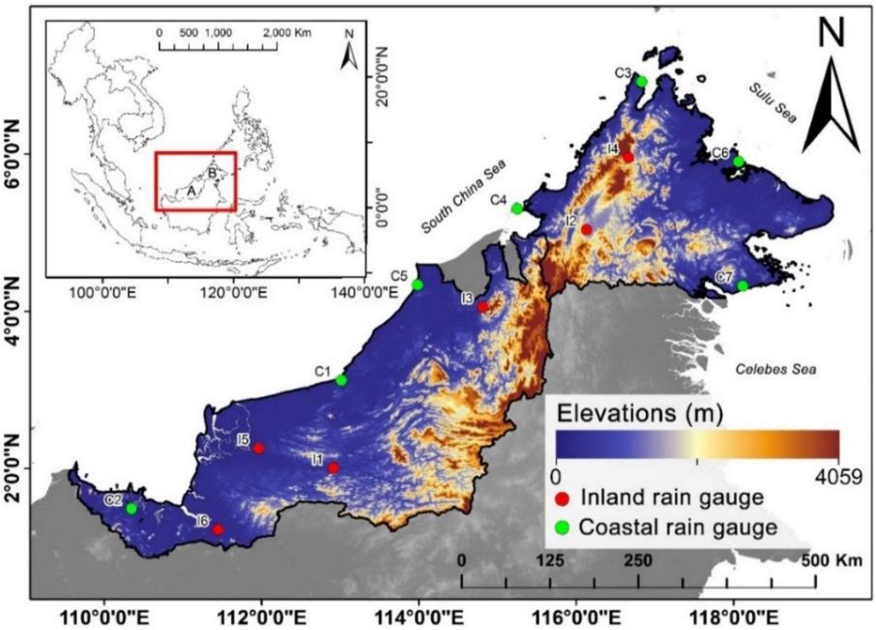

Figure 1: Map of the study area, rain gauge distribution for respective type, digital elevation model (DEM), as well as Sabah and Sarawak state location within Borneo Island.

2.2 TRMM AND GPM Satellite Precipitation: The remote sensing observation of the rainfall data is in monthly basis. They came from two level three satellite precipitation namely TRMM Multi-Satellite Precipitation Analysis (TMPA) 3B43 and Integrated Multi-satellitE Retrievals for GPM (IMERG) 3IMERG, hence forth called IMERG and TRMM in this paper respectively. The development of these satellites is a joint mission between Japan Aerospace Exploration Agency (JAXA) and National Aeronautics and Space Administration (NASA). Table 1 shows the comparison description of the data acquisition for both satellites.

Table 1: Satellite precipitation comparison on detail of TMPA and IMERG used in this study.

Detail	TMPA	IMERG
Temporal Resolution (Used)	March 2014-April 2015	
Spatial Resolution	0.25° x 0.25°	0.10° x 0.10°
Coverage (Available)	50N° – 50°S	60°N – 60S°
Format	NetCDF	
Precipitation Unit	Milimeter per Month (mm/month)	
Data name configuration	TRMM 3B43	IMERGM (final run)
Data Source	TMI, AMSR, SSM/I, SSMIS, AMSU, MHS, *MerOp-B*, TCI	TMI, AMSR, SSM/I, SSMIS, AMSU, MHS, SAPHIR, ATMS, AIRS, TOVS, CRIS

The TRMM contain with instruments such as Precipitation Radar (PR), TRMM Microwave Imager (TMI), Visible and Infra-Red Scanner (VIRS), Cloud and Earth Radiant Energy Sensor (CERES) and Lightning Imaging Sensor (LIS). Meanwhile, the GPM carries the GPM Microwave Imager (GMI) and Dual-Frequency Precipitation Radar (DPR). Compared to five sensors onboarding the TRMM, the GPM contains with only two sensors. However, the GPM preceded TRMM in term of sensor capability where it delivers more advance technology for similar sensor type and wider coverage as well as in 3-dimension measurement. Moreover, the GPM has an advantage where it is designed as a Core Observatory that synchronizes data acquisition with constellation of satellites to ensure uniformity rather than operating as a singular form in a manner TRMM operates (Kim *et al.*, 2017).

2.2.1 TRMM: The TRMM was launched from Tanagashima Space Center on 1997. The data availability was from the year 1998 until 2015. TRMM data product consists of 3 levels with the naming system of 3B43 is interpreted through "3" for level 3, "B" for multiple sensors, and "43" for monthly. In short, there are four phases involve in the processing to generate the 3B43 data product. It begins with 1) microwave estimates calibrated and combined, 2) the matched infra-red precipitation estimates were computed together with the previous microwave phase, 3) the microwave and IR data were merged together and 4) resizing the temporal scale to monthly basis (Huffman *et al.*, 2007).

2.2.2 IMERG: The GPM was launched from the same place with TRMM. Beginning in the year 2015 and onwards, the data was available for the public to use. Processing phase for the IMERG is quite similar to the TRMM, for example, having multiple satellites sensor as input. However, due to the sensor and mission improvement, the altered algorithm was including the changes in the land while maintaining the measurement for the ocean area. The processing steps are as follows: 1) using the improved multi-channel physical algorithm the multi satellite input were inserted to compute the rainfall profile. 2) the spatial and temporal resolution were increased by including supporting data from PERSIAN-Cloud Classification System (PERSIANN-CCS) recalibration scheme and Climate Prediction Centre (CPC) Morphing-Kalman Filter (CMORPH-KF) with Lagrangian time interpolation technique, 3) data from Global Precipitation Climatology Centre (GPCC) in merged for accuracy improvement (Huffman *et al.*, 2015).

2.3 Ground Precipitation: Measurement for rainfall on the ground was done using the rain gauge. The data was provided by the Malaysia Meteorological Department. Initially, the time of collection was 0800 local time in daily basis and was converted to monthly to match the satellite temporal resolution. A total of 13 stations were used (Table 2) with 7 stations (54%) designated for coastal and 6 stations for inland (46%). Figure 1 shows the distribution of the rain gauge and their categories while Table 2 lists the ID label with respect to the categories

Table 2: Rain gauge ID label according to their usage either for coastal (C) or inland (I).

ID	Name	State	Height (m)	Category
C1	Bintulu	Sarawak	24.3	Coastal
C2	Kuching	Sarawak	20.9	Coastal
C3	Kudat	Sabah	3.5	Coastal

Table 2: Cont.

C4	Labuan	Sabah	27.9	Coastal
C5	Miri	Sarawak	17	Coastal
C6	Sandakan	Sabah	12.1	Coastal
C7	Tawau	Sabah	17.5	Coastal
I1	Kapit	Sarawak	35	Inland
I2	Keningau	Sabah	319	Inland
I3	Mulu	Sarawak	26.2	Inland
I4	Ranau	Sabah	501	Inland
I5	Sibu	Sarawak	30.9	Inland
I6	Sri Aman	Sarawak	9.6	Inland

2.4 Satellite-Ground Validation: Three major statistical approaches were used in this study, namely; (1) Bias type: Bias (b), Mean Absolute Error (MAE), Absolute Percentage Bias (APB); (2) Error type: Root Mean Square Error (RMSE), Mean Absolute Error (MAE); and (3) Correlation type: Correlation Coefficient (r) and Nash-Sutcliffe Coefficient (N_r). Each approach of validation has advantage to expose separation of values, error trend, and gap of value relative to satellite-ground data measurement. The computation of the aforementioned statistical approaches are as follows:

$$b = \frac{\sum_{i=1}^{n}(R_S - R_G)}{n} \quad (1)$$

$$APB = \frac{\sum_{i=1}^{n}|R_S - R_G|}{n} \times 100 \quad (2)$$

$$RMSE \sqrt{\frac{\sum_{i=1}^{n}(R_S - R_G)}{n}} \quad (3)$$

$$MAE = \frac{\sum_{i=1}^{n}(R_S - R_G)}{n} \quad (4)$$

$$r = \frac{\frac{1}{n} \times \sum_{i=1}^{n}(R_G - \overline{R_G}) \times (R_S - \overline{R_G})}{\left(\sqrt{\frac{n \times \sum_{i=1}^{n} {R_G}^2 - (\sum_{i=1}^{n} R_G)^2}{n \times (n-1)}}\right) - \left(\sqrt{\frac{n \times \sum_{i=1}^{n} {R_S}^2 - (\sum_{i=1}^{n} R_S)^2}{n \times (n-1)}}\right)} \quad (5)$$

$$N_r = 1 - \frac{\sum_{i=1}^{n}(R_S - R_G)^2}{\sum_{i=1}^{n}(R_G - \overline{R_G})^2} \quad (6)$$

where;
R_G is rainfall from the ground rain gauge, R_S is satellite rainfall from the satellite and n is count of the data set.

3.0 RESULTS AND DISCUSSION

3.1 Spatial Validation (Coastal and Inland)

The spatial comparison were done in separated location of coastal (C) and inland (I). Meanwhile the temporal refers to the statistical evaluation that has been converted into monthly basis for both of the satellites. Firstly, initial analysis was conducted by analysing the coastal and inland only by clustering IMERG and TRMM together. Between the coastal and inland in Table 3 (IMERG C vs. TRMM C and IMERG I vs. TRMM I), the C area performed better than the I. For instance, the r is high at 0.9, APB at ~20%, and more importantly, the usability in coastal hydrology (Nr) is consistently high at 0.8 rather than low (Nr inland = 0.6 and 0.5) for TRMM and IMERG. This suggests that the satellite data can be used for coastal study and IMERG could replace the TRMM successfully in the general coastal studies. Similar study was carried out in Asia by Liu (2016) where it shows that in the ocean, the IMERG have small differences over TRMM. However, the study was analysing the ocean and land rather than coastal and inland, which is quite similar but not exactly illustrating the same criteria. Thus, the result differences could be due to different locations separability.

Table 3: TRMM and IMERG statistical validation result using b, MAE, RMSE, APB N*r* and R, while the coastal and inland are labelled as C and I, parallel with label used in Figure 1.

Spatial Type	**Satellite Type**	**Statistical Approach**					
		BIAS (*b*)	**MAE (mm)**	**RMSE (mm)**	**APB (%)**	**(N*r*)**	**R**
Coastal (C)	IMERG	7.138	49.985	74.689	22.177	0.847	0.927
	TRMM	-6.833	46.818	71.495	20.772	0.860	0.935
Inland (I)	IMERG	6.932	68.092	85.977	27.745	0.659	0.813
	TRMM	25.758	75.862	94.568	30.911	0.587	0.790

Figure 2 depicts that the changes on overall pattern for bias, error and correlation type are consistent for both satellites in inland and coastal by having similar trend. This situation is however resulted with the *b* IMERG has slight opposite difference trend at 0.206mm, which is minimal. In spite of the opposite direction, huge *b* can be spotted between the coastal and inland in Figure 2 a) for TRMM compared to IMERG, where the value of -32mm indicates TRMM low capability in adapting the inland effect. The increment and decrement could be clarified at Figure 2 b) with all value are measured in a single positive manner in ΔMAE. Consequently, large differences in the ΔMAE for TRMM in costal versus inland (-29mm) suggest that the error exist in both positive and negative values are higher than IMERG.

Meanwhile, in Figure 2 c), the Δ*r* and ΔN*r* show the IMERG small differences in coastal and inland (C vs. I) at Δ*r*=0.18 and ΔN*r*=0.11 compared to TRMM at Δ*r*=0.27 and ΔN*r*=0.14 indicating that IMERG had reduced the gap between satellite-ground data. This behaviour could be due to the effect of GPROF2010 algorithm used by TRMM compared to GPROF 2014 used by IMERG where it was able to capture more data in the transition between land and the coastal area. Furthermore, the capability of GPM sensor input for IMERG to collect data in low and high microwave frequency (37 GHz) provides high sensitivity in distinguishing between coastal and inland hydrological elements altogether.

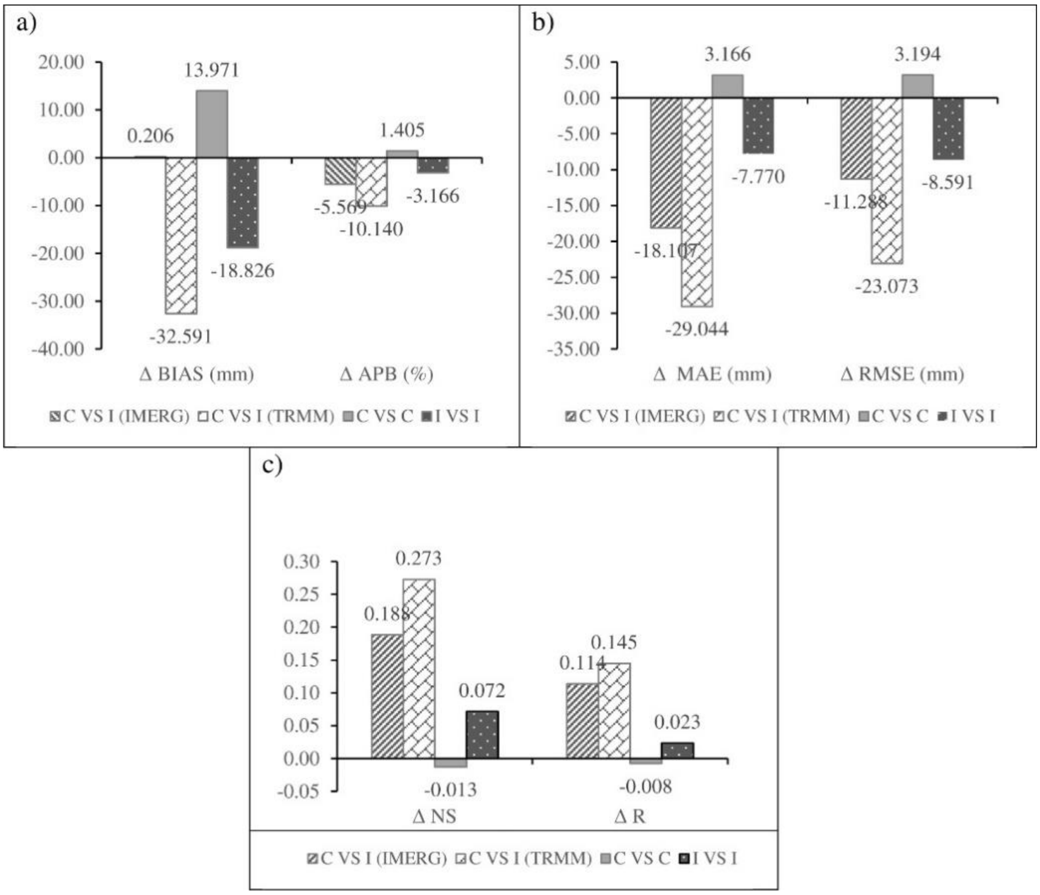

Figure 2: Statistical validation bar chart, a) bias type (*b* and APB), b) error type (MAE and RMSE) and c) correlation type (N*r* and *r*) for the coastal (C) and inland (I); they are plotted with two comparison basis: coastal vs. coastal signify differences between TRMM and IMERG in coastal area and; coastal vs. inland, signify TRMM differences in coastal and inland; and these is similarly applied to the IMERG.

Further investigation in the monthly rainfall changes distribution map in Figure 3 on IMERG over TRMM displays another significant change in Nov, Dec, Jan 2015 (Figure 3 i)-k)). The changes reduction of ~500-300mm (blue to purple colour) were mostly concentrated on the ocean and the trend stopped at near coastal. This suggests that the effect of topographic as well as the new satellite adapting rainfall on land mass transition was better than the previous generation. Meanwhile, in Figure 3 a)-c), the distribution changes result for coastal and inland are approximately the same (~100-200mm). This could be due to the effect of the temporal (seasonal) of the inter-monsoon behaviour where the rainfall pattern would be less in density and frequency. Repeated scene of the inter-monsoon in the next year cycle can be seen in Figure 3 m)-n) as it provides support to the inter-monsoon effect of the pattern of the previous same date. Visual inspection on all months provide another constant trend in Sabah, where the steep elevations near the shore (Figure 1) create a substantial segment of rainfall difference around -50 to 100mm (yellow and green). This spatial trend is supported by coastal to inland differences found by Tan and Santo (2018) where the pattern of coastal region were solidly captured by six satellite precipitation used in their study. On the other hand, Kim *et al.* (2017) in Korea and Mayor *et al.* (2017) in Mexico found that variation on the bias are depended to the geographical structure.

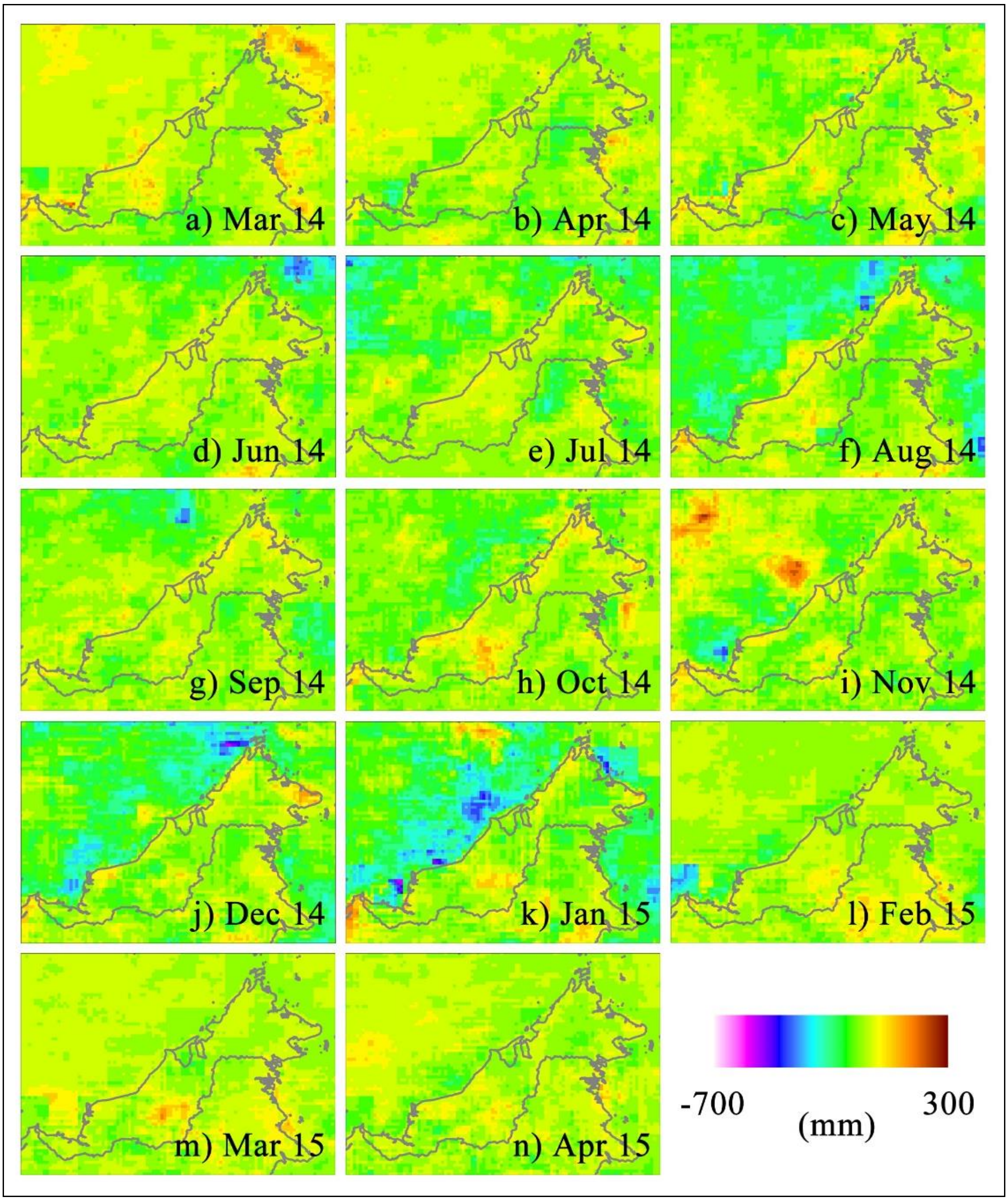

Figure 3: Maps of monthly rainfall changes in overlapped period of TRMM and IMERG.

3.2 Temporal Validation (TRMM and IMERG)

Temporal validation of the statistical evaluation were done by clustering Sabah and Sarawak together and the only characteristic considered were satellite and spatial where they were separated into their respective month. In Figure 4 a)-f), coastal rise and fall overall trend are almost in similar for both satellite. Despite the similarity, in coastal area, the bias type (Figure 4 a)-b)) shows that IMERG tended to overestimate in May, June, July during the SWM. Small gap between IMERG and TRMM in APB could be due to the small rainfall measurement where it reduced the data available to compute the value in percentage. Interestingly, IMERG APB yielded stable value (<~ 60%) in all months except in December while TRMM overestimate two more months which indicates that TRMM has less adaptability in high rainfall than IMERG.

Meanwhile, in the inland, the highest *b* occurred from TRMM at ~60mm rather than IMERG at ~40mm in November during inter-monsoon. Reduction of 30% signifies positive improvement in the *b* of IMERG. However, while in the same month for coastal, the value is ~10mmm (IMERG) and ~30mm (TRMM) indicates that the reduction occurred in the inland, it is not in the same scale for the coastal (~60%). This can be seen in March where *b* value for TRMM inland was 20mm more accurate than IMERG. Such value could be appear due to capability of TRMM to capture a dynamic of initial inter-monsoon in single platform sensor compared to IMERG. Thus, although the IMERG performed in certain months, there were still several months that TRMM performed better than IMERG.

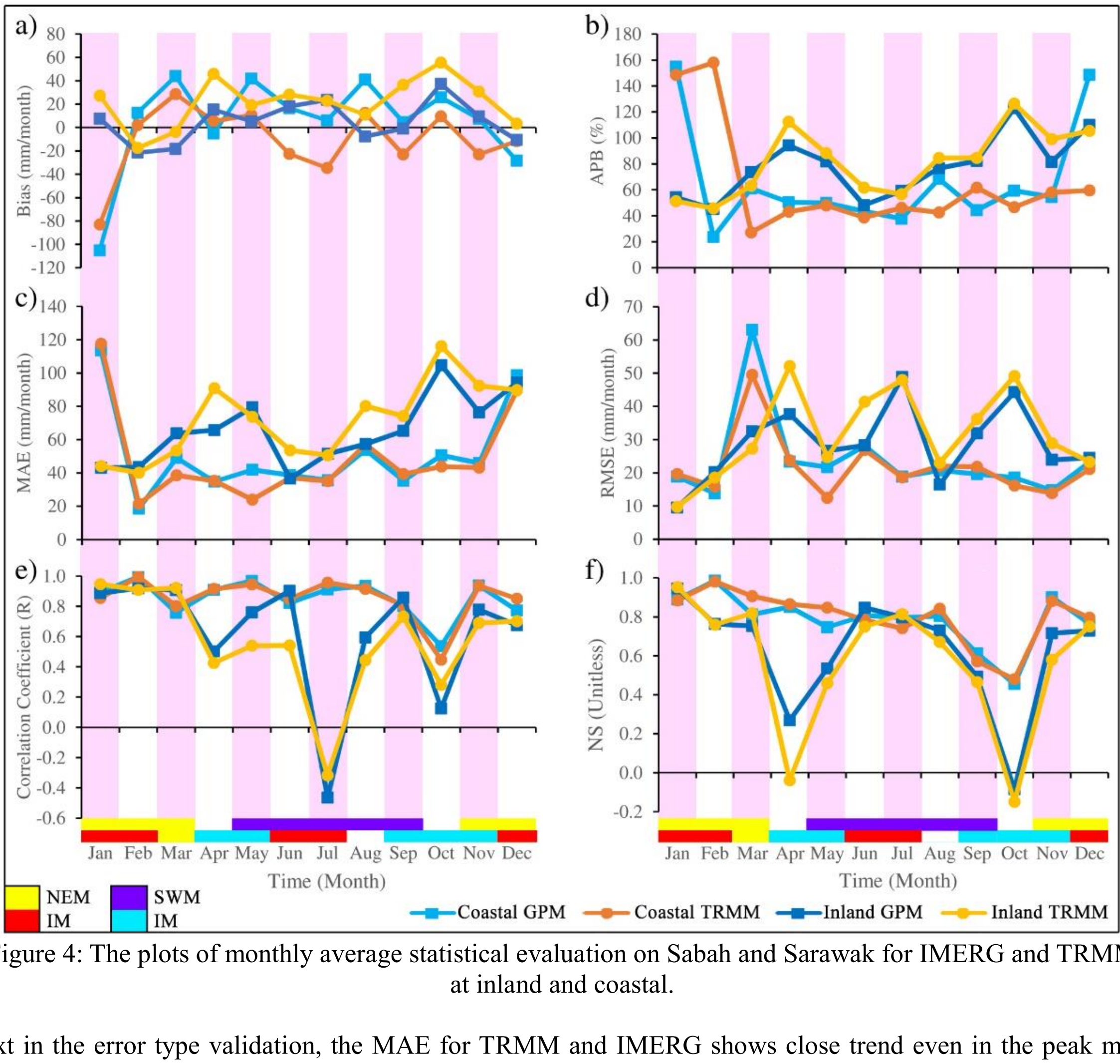

Figure 4: The plots of monthly average statistical evaluation on Sabah and Sarawak for IMERG and TRMM at inland and coastal.

Next in the error type validation, the MAE for TRMM and IMERG shows close trend even in the peak monsoon season in December compared to bias type. However, the MAE had opposite direction than the RMSE. For instance, in July where the value was at low (~40-60mm) for both satellites and validation type, the RMSE shows the second highest reading (~50mm) compared to other months. Therefore, they should be analysed inversely. The nature of MAE in changing the negative value of error and computing it in averaging might create a different trend compared to RMSE. The error in the land occured at high rate in May and Oct could be due to the beginning and the end of

SWM plus the orographic effect (Sharifi *et al.*, 2016). Rainfall dynamic in the tropic might create a hit and miss between sensor used to collect and confirm a rainfall occurrence. The tropic are known to have thick cloud in most of the rainfall region and during the monsoon transition, the cloud might exist without rainfall occurrence thus leading to increase of error.

On the correlation validation in Figure 4 e)-f), the strength of the relationship between the ground data measurement and satellite generally again performed similarly. However, high correlation for both TRMM or IMERG on inland or coastal for each month starting from Jan to April would be found if further analysed. The correlation was then drop beginning in April, where the inter-monsoon started and rose up until Jun, where then a sudden drop took place in July. The trend from Jan to July for N*r* and *r* were consistently towards each other however in July, the value for inland below 0 indicates inverse relationship. In September, at the end of the SWM, the value spiked again for *r* (0.8) but not for N*r* (0.8). From October onwards, the trend for both correlation validation began to synchronize again. The usability of both data for hydrology were only low in April and October. This suggests that the inter-monsoon does affect satellite data performance. Additionally, in the same month, the coastal performed better at ~0.8 (April) and ~0.6 (October).

By analysing Figure 2, 3 and 4 together, it can be seen that despite the differences in term of bias, error and correlation, the performance were not affected by satellite type alone. Variable such as the spatial variability between inland and coastal should be taken into account when using the IMERG data after the decommissioned of TRMM. Another variable that need to be considered is the temporal separability where the satellite would not perform well for all months and would require refined localized calibration for better result. In the temporal resolution, the nature effect such as seasonal (Hashim *et al.*, 2016; Petersen *et al.*, 2002; Varikoden *et al.*, 2010), and their elevation structure towards rainfall behaviour (Sharifi *et al.*, 2016) should not be left out during the analysis so that the anomaly detected would still be within the acceptable range of the localized user knowledge. Moreover, increment on spatial resolution in IMERG does provide advantages in distinguishing the coastal and inland compared to TRMM where more data variation were observed (figure 3). The variation existed in form of the pixel variation indicates effect of TRMM pixel size input (0.25°) and the opposite (small pixel size = 0.1°) from IMERG. Therefore, more pixelate area and colour variation due to IMERG input would provide deeper understanding on the performance of both satellites.

4.0 Conclusion

The statistical approaches in the validation of TRMM and IMERG together within the scope of spatial (inland and coastal) and temporal (monthly) is important for further usage of satellite precipitation data especially IMERG. Although IMERG is meant to replace the TRMM, this study shows that TRMM still holds an advantage in some places at coastal and inland within certain months. While precipitation is known to have variation and distribution globally, the spatio-temporal map shows local effect on both satellites such as difference in coastal-inland, elevation and orography effect. Compared to inland, near coastal is more stable for both satellites. Meanwhile, the IMERG inland is proven to be superior than the TRMM due to algorithm enhancement. Even though IMERG performing significantly better in some statistical evaluations, the TRMM still performs in several months due to seasonal characteristic. Temporally, the decommissioned TRMM past data will provide long term benefit for the IMERG for future study. Spatially, the IMERG size provides more detail than the TRMM thus widening the application of the data in future. Information gained from this study could benefit various applications including land hydrology, coastal, and nearshore areas in the tropical region especially Southeast Asia. Moreover, with climate the climate changing rapidly, the rainfall condition can be monitored under wide area from global to local scale using previous decommissioned satellite together with new generation satellite. The influence of precipitation especially rainfall towards shoreline changes, soil erosion, biophysical changes, water supply, physical oceanography, biophysical characteristic, and anthropogenic activity can be investigated in more complete view altogether in the future.

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