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# A Conceptual Framework for Classifying the Tropical Rainfall Using the Satellite Radar Imageries

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**Abstract:** This paper developed the conceptual framework to classify the predominant mesoscale (4-100km) to synoptic scale (100-1000km) of rainfall in humid tropical environment using satellite radar imageries. The current classification has limitations to precisely describe the dynamics variability of such rainfall categories. At present, the classification scheme only referred to the intensity at fixed temporal scale, in which resulted generalization and misrepresented of the two rainfall categories. In addition, there are no mutual consensus of rainfall classification in the tropics and every organization or responsible authorities of a region or countries use or initiate their own classification references. As a result, there are insufficient precaution, preventive measures, policy, and adaptive initiatives against those extreme rainfall events. Improving the present classification class would provide information on various tropical storm class detection and subsequently increasing the hydro-related disaster and risk assessment. Therefore, to anticipate this issue, revisit of the present classification scheme by considering both spatial, intensity and temporal elements are required. Precipitation radar imageries; both from ground and space satellite had advent to high spatial and temporal resolution with approximately 4-5km at nadir at 10-15 minutes interval. This study initiated the improved classification scheme of mesoscale and synoptic scale rainfall in humid tropics using the open-source data from the new generation satellite precipitation of Feng Yun of China (FY-4B). The initiated spatial profiling framework would have four phases including; (1) Data acquisition & preparation, (2) Quality assurance, (3) Developing the scheme for mesoscale and synoptic scale rainfall reclassification, and (4) Implementation of the scheme and testing. The output of this framework is the common and significant class for tropical mesoscale to synoptic scale rainfall at various sub-daily interval. The developed conceptual framework would contribute in deeper understanding on the emerging changing tropical rainfall, improve rainfall induced disaster management, and environmental adaptation.

**Keywords:** Feng Yun, Mesoscale, Synoptic Scale

## 1. Introduction

Climate change in humid tropics occurred significantly through the changing of weather pattern particularly rainfall at sub-daily scale. The changes occurred at complex dimension of space and time; for instance, the increasing occurrences of short-lived rainfall but with extreme intensity. This rainfall change has impacted the environment, causing various catastrophes including flash flood, traffic congestion, reduce visibility, and even public health due to increased heat-illness risk (e.g., heat stroke) and respiratory related illness (e.g., flu, fever) (e.g., Si et al., 2022; Al-Qadami et al., 2024). Revising and implementing an effective policy by the government is mandatory to anticipate those concerns (Jee et al., 2024). However, such action is constraint by the underreporting of the rainfall changes especially in the humid tropics (Hulbert & Gupta, 2015). Among the major reasons for that is the absence of the effective rainfall classification and definition that includes spatial, intensity, and duration of the storm or rainfall events.

The spatio-temporal characteristics of rainfall in humid tropics is highly varied and require at least three aspects to fully represent it; (1) duration, (2) intensity, and (3) spatial coverage. Present progress in rainfall classification was limited to either single aspect description or dual aspect description. At present, common classification is primarily based on intensity. There was no consensus on the standard

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rainfall class and many responsible bodies or meteorological agencies adapt based on their own data, research or internal regulations (AMS, 2014; Sofiati & Nurlatifah, 2019; MMD, 2024). There were differences in term of value and definition of the rainfall class. For instance, 20mm/hr rain is classified as violent by the BMKG or Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG) (BMKG, 2014), heavy by Malaysian Meteorological Department (MMD, 2024), and medium by the American Meteorological Society (AMS, 2014). In addition, the quantitative range of values also were largely varied. Taking for example, the very light rain that is very common in humid tropics is considered to be less by 10mm/hr by the AMS, while the BMKG defines it to be from 0.1 to 1.1mm/hr.

Meanwhile, for the rainfall duration and spatial coverage aspect, the definition and classification were done independently from each other. In describing rainfall duration, although there is existing term for various rainfall duration, it is less robust and less detail (e.g, Roca & Folliau, 2020). For instance, the rain event that happen rapidly (< 1 hour) is referred as short-lived precipitation (Al-Mamun et al., 2018), but for the rain event that occurred more than that (2-8 hours) is classified as medium lived (Tang et al., 2022). The variation of rainfall intensity for such broad time interval (2-8 hours) can be great in humid tropics. Almost a same situation occurred with classifying the spatial coverage aspect of the rainfall. Despite there were existing class of microscale, mesoscale, synoptic and planetary, the values break within the class need revision (Bonell et al., 2005; Yuanjian et al., 2021). This is especially for the mesoscale (4-100km) and synoptic scale (100-1000km) whereas the gap between the class is relatively large and sub-division is suggested to fully represent the sub-variation of spatial rainfall patterns. It is understood that previously the classification made either based on rain gauges information or coarse resolution satellite imageries (~20 km grid), thus limiting the detail information. Conceivably, the classification can be revisited and enhance by employing appropriate precipitation data.

The appropriate precipitation data to serve the needs of high spatial and temporal is the ground precipitation radar. Nonetheless, dealing with such data constraints by several factors includes; data purchasing policies and high costs (Datarade, 2024), data sharing bureaucratic obstacles (Michelson et al. 2013), high-performance computing resources and time-consuming processing due to their large volume and complexity (Ajima et al. 2018; Dash et al. 2022). With the advent of the present satellite precipitation data that provides regularly at very high temporal (15 minutes), high spatial (4km), and decent accuracies, it then allows an in-depth identification and categorization of the highly dynamics sub-daily tropical rainfall (Xian et al., 2021; Yang et al., 2018). Therefore, using this satellite data as substitute or alternative could offer promising opportunities to perform rainfall classification seamlessly.

Based on the above-mentioned discussion, several research gaps can be formulated as well as initiatives to anticipate it. First is the need to establish more intensive rainfall class for the equatorial humid tropical region; in order to effectively represent the rainfall condition and severity. The second gap is the limitation of single perspective in classifying rainfall; mostly intensity. The third gap is the limitation of the ground weather precipitation data processing due to its processing complexities, distribution and sharing policies which hindered their practical utilization. Perhaps the key to address the gap is the inclusion of the three elements; intensity, duration, and spatial extent, with the use of the newly high temporal satellite precipitation data as substitute to obtain new rainfall class that suits the equatorial humid tropics. This anomalous attempt to challenge the status quo of rainfall classification in humid tropics would contribute to notable categorization and understanding of the sub-daily tropical rainfall.

To address the research gap, this paper had only one objective; to develop a conceptual framework in improvising the classification of rainfall in humid tropical environment using radar imageries. The new rainfall class would incorporate three major elements; (1) intensity, (2) duration, and (3) spatial extent. Types of rainfall that will be taken into account is sub-daily rainfall (<9 hours duration) with the size of spatial extent from 4km (mesoscale) to 1000km (synoptic). The data that will be used is the recently released open-source data from the new generation satellite precipitation of Feng Yun of China (FY-4A and 4B) (Xian et al. 2021; Du et al. 2024). The Geographical domain for the sampling procedures is to be in the equatorial humid tropical basin; where low-level convergence is actively occurs. The developed conceptual framework would contribute in deeper understanding on the emerging changing tropical rainfall, improve rainfall induced disaster management, and environmental adaptation; suitable for policy makers related to hydrological and water issues, as well meteorologist and hydrological practitioners.

## 2.0 Concept of spatio-temporal classification scheme of the tropical rainfall using satellite precipitation images

The main motivations to develop the framework to reclass the tropical rainfall using the satellite precipitation data includes to provide a comprehensive and inclusive guidance in understanding rainfall events in humid tropical region. The sub-daily rainfall has large significance and emerging influence on the overall rainfall variation especially in Intertropical Convergence Zone (ITCZ)(Varikoden et al. 2011; Ancy et al. 2024). In addition, sub-daily rainfall variation largely influencing the localized weather dynamics in humid tropics (Jackson et al. 2025). Consequently, having standardized class that represent the dynamic tropical rainfall especially the short lived (< 1 hour) would significantly deepen the understanding and knowledge. In addition, it provides accurate characterization of the common local rainfall scenario and provide better tools for accurate analyses and reporting. Utilizing the publicly access satellite precipitation images enabled the work to be perform with cost effective and yet maintaining important information.

Because rainfall in humid tropics was highly dynamic via spatial and temporal scale, therefore, it is ought to be represented by taking into consideration of the three elements, which includes duration, spatial coverage, and intensity. Nonetheless, due to the limitation of several factors, specific requirement and condition need to be emphasized. First, the satellite spatial grid size possesses ~4km resolution, then the microscale rainfall (<2km) identification is not permissible. Secondly, the intended purpose of the reclassification scheme is to provide from municipal to at least nationwide scale management. Therefore, considering the acreage and common rain types that occurs on those management scale; it is best represented by the mesoscale weather pattern (4-100km) and synoptic (100-1000km). It is expected that the newly introduced reclassification scheme could precisely represent

majority of the rainfall population locally; as sub daily rainfall is merely dominant in humid tropics (Biasutti & Yuter, 2013; Ganguli 2023; Noguchi et al. 1996). In addition, the areas concerned would be on the land and coastal only; whereas offshore zone is juridically under international law.

Regarding the second elements, which is the duration, the targeted scope is the sub-daily rainfall which means rainfall that occur less than 12 hours consecutively. As the satellite data offers 15 minutes interval data, introducing the sub-hour class is plausible. It is recommended that several sub-daily classes were established as highlighted in Table 1. It covers from sub-hour or known as short lived rainfall to half daily rainfall. Number of classes is proposed to be determine based on samples measured at specific observation period. Suggested period is to be at least covering specific rain period or monsoon period which are the most common seasonal drive of heavy rainfall. On the third elements, which is the intensity, the proposed approach is pretty straightforward whereas it covered from light to violent rainfall. In this proposed reclassification scheme the class also will be assigned based on the measured samples.

Conceivably, the most complex process is the approach on how to classify the rain events into the meaningful and accurate classes following the three elements; duration, spatial, and intensity. Because every rain events have specific onset and offset, it is best to define or reclass them into specific duration first. Hence, common rain events in tropics were short lived (< 3 hours) or very short lived (<1 hour). Subsequently it was followed by identifying the spatial extent of the rain events that occurred at the same period. Upon classifying the spatial extent, those pixels who are belong to the same duration and spatial extent, will be determine their specific average intensity. Those classes that exists will be named and labelled accordingly. The proposed naming system is to utilized its 3 elements details, where D represents duration, S represents spatial extent, and I represent intensity. Figure 1 simplify the concept embedded in the proposed tropical rainfall reclassification scheme.

Table 1. Three proposed elements in the reclassification and its description

| No. | Dimension | Description |
|---|---|---|
| 1 | Duration | Very short-lived rainfall (< 1 hour) |
| | | Short-lived rainfall (1-3 hours) |
| | | Medium-lived rainfall (3-6 hours) |
| | | Long-lived rainfall (6-9 hours) |
| | | Half daily rainfall (> 9 hours) |
| 2 | Spatial Extent | Mesoscale (4 - 100km) |
| | | Synoptic scale (100 - 1000km) |
| 3 | Intensity | Light to Violent (1 to more than 100mm/hr) |

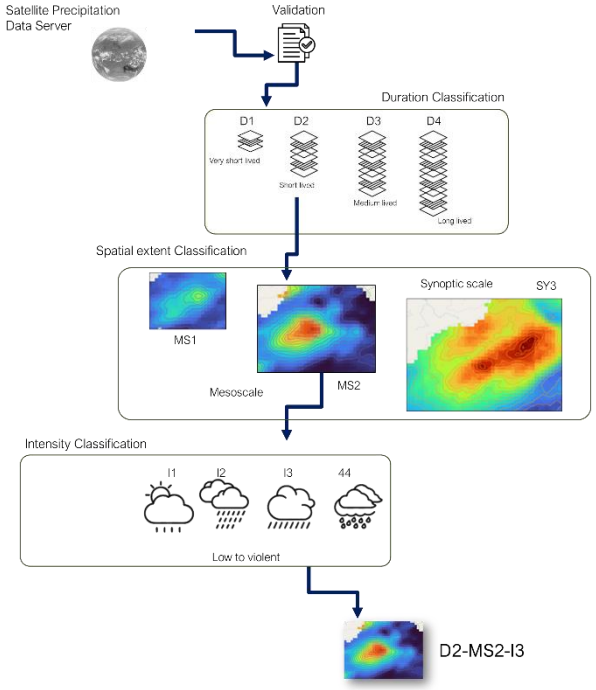


**Fig.1-Conceptual diagram of the reclassification framework**

**3.0 The framework of the spatio-temporal classification scheme of tropical rainfall using satellite precipitation images**

There are five phases in the framework; (1) Data acquisition & preparation, (2) Quality assurance, (3) Developing the scheme for mesoscale and synoptic scale rainfall revised class, and (4) Implementation of the scheme and testing. The scope and brief description of each phase were shown in Table 2 and the flow of methodology shown in Figure 2.

Table 2. Summary of the framework components and phase.

| No | Phase | Description |
|---|---|---|
| 1 | Data acquisition & preparation | • Data retrieval from the server<br>• Geometric rectification<br>• Geometric subset<br>• Preparing various sub-daily rainfall images |
| 2 | Quality assurance | • Root mean square error (RMSE)<br>• Bias calculation<br>• Correlation<br>• False Alarm Ratio (FAR)<br>• Probability of Detection (POD)<br>• Nash Sutcliffe Efficiency (NSE) |
| 3 | Developing the scheme for mesoscale and synoptic scale | • Factor 1: Duration<br>- Jenks Natural Breaks Classification<br>- Quantile Classification |

| No | Phase | Description |
|---|---|---|
| | rainfall revised class | • Factor 2: Spatial Coverage<br>- Clustering analysis<br>• Factor 3: Intensity<br>- Kernel average calculation |
| 4 | Implementation of the scheme and testing | • Execution of the reclassification scheme<br>• Cross tabulation analysis<br>• Reporting |

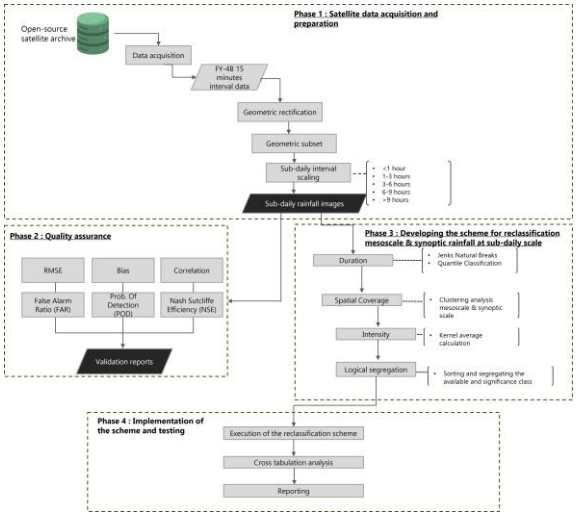


**Fig.2-Proposed framework**

*Phase 1: Satellite data acquisition and preparation*

In the first phase, the satellite precipitation data were obtained from the National Satellite Meteorological Agency of China (NSMC) and China Meteorological Administration (CMA) through their official web server. The selected product is the FY-4B, which the next-generation Chinese geostationary satellite equipped with sensors such as the Advanced Geosynchronous Radiation Imager (AGRI) and Lightning Mapping Imager (LMI). The QPE product provides precipitation estimates based on the integration of multiple spectral bands from IR and microwave observations, enabling near-real-time rainfall retrieval at high temporal frequency (Guan et al., 2021). The spatial resolution of the dataset is approximately 0.04° with 15 minutes temporal interval, making it an ideal option for high-frequency monitoring of rainfall variability in the tropics.

Upon the retrieval the data will undergo geometric rectification in order for it effectively supported by Quantum GIS environment based on the given global orbital coordinates and geometric references. It will be projected into the famous World Geodetic System 84 (WGS84) coordinates or referred as EPSG4326, European Petroleum Survey Group in the QGIS software systems. The geocoded precipitation images were then subset into our area of interest by masking out the unwanted pixels. This process is important to reduce the processing burden as number of samples increased (i.e., daily, monthly, etc.).

The subsequent process is to produce the sub-daily rainfall images from these 15 minutes product. The purpose of this creation is to fit the nature of rainfall event itself, which it must have onset and offset. Thus, by knowing the exact duration of a rainfall event, then the intensity and spatial coverage can be determined. There are five types of sub-daily rainfall period which includes 1) <1 hour (very short lived), 2) 1-3 hours (short lived), 3) 3-6 hours (medium lived), 4) 6-9 hours (long live), 5) >9 hours (half daily). The product for each duration class is by direct averaging of all the rainfall images within that period.

*Phase 2: Quality assurance*

In the second phase, the sub-daily rainfall products will undergo quality assurance process. It needs to be validated to determine its accuracy and performance. This is because based on concurrent evaluation at global scale, despite its potential to represent precipitation, it experienced several limitations especially the underestimation or mixed bias for very heavy or extreme rainfall events, meaning extreme convective peaks can be missed or underestimated by the retrieval and overestimation of light precipitation and underestimation of very heavy rainfall in some cases, (Zhu et al. 2022; Sun et al. 2022). Therefore, localized evaluation and calibration is required as part of quality assurance. This evaluation will utilized rain gauge as main reference as practiced by many studies. The suggested duration is to match the satellite temporal scale which is 15 minutes. Nonetheless, the availability of rain gauges data at such scale is difficult. Often, rain gauges data were supplied and archived at hourly basis.

To conduct this validation, six statistical indicators were recommended. The selection of these statistical indicators was based on best practices by existing and prominent studies that related with quality assurance analysis of satellite precipitation (Paluba et al. 2025; Omay et al. 2025). The six indicators are 1) Root mean square error (RMSE) or sometime referred as average differences (AD), 2) Bias, 3) Correlation (either parameteric or non-parametric), 4) False alarm ratio (FAR), 5) Probability of detection (POD), and 6) Nash Sutcliffe Efficiency (NSE). Each of the statistical indicators provides specific evaluation as follows;

(a) Root mean square error

The purpose of the Root Mean Square Error or Average Difference is to measure the deviation between the estimated satellite rainfall values against the corresponding rain gauge measurement. The error quantifies how much rainfall differences in the unit of measurement based on the chosen interval; common unit for satellite rainfall-rain gauge cases is millimeter per hour (mm/hr) or millimeter per day (mm/d).

$$RMSE=\sqrt{\frac{1}{n}\sum_{i=0}^{n}(P_{sat,\,i}-P_{obs,i})^2} \qquad \text{Eqn. (1)}$$

where $P_{sat,\,i}$ is the satellite-estimated rainfall, $P_{obs,i}$ is the observed rainfall, and *n* is the number of observations. Lower RMSE indicates higher accuracy.

(b) Bias

Bias measure provides measurement on whether the satellite precipitation overestimate or underestimate the actual rainfall detected at ground level. The higher the bias, >1 indicate

satellite overestimation, while <1 indicate underestimation (Li et al., 2021).

$$A = \frac{A+B}{A+C} \quad \text{Eqn. (2)}$$

where A is where both satellite and rain gauge identified the rain events at the same time, B is the cases where satellite detect the precipitation and rain gauge does not, and C is the cases where the rain gauge identified the rain but the satellite does not.

(c) Correlation

Measure the degree of relationship between the satellite rainfall and rain gauges measurement. Most of the time, Pearson correlation was used under the assumption that the distribution is normal. Nonetheless, there are possibilities that rainfall data especially during low rainy days or drought period, were experiencing non-normal distribution. In this case, opting for non-parametric test is suggested like Mann-Kendall, Spearmann, or Kolgomorov-Smirnov. High correlation means the satellite rainfall and rain gauge were highly correlated and vice versa. Having decent correlation can be critical for any satellite precipitation data to indicate its reliability of rainfall estimates. The most common Pearson correlation is described as follows;

$$r = \frac{\sum (P_{sat,\,i} - \bar{P}_{sat})\,(P_{obs,i} - \bar{P}_{obs})}{\sqrt{\sum (P_{sat,i} - \bar{P}_{sat})^2 \cdot \sum (P_{obs,i} - \bar{P}_{obs})^2}} \quad \text{Eqn. (3)}$$

where $P_{sat,\,i}$ is the satellite-estimated rainfall, $P_{obs,i}$ is the observed rainfall, $\bar{P}_{sat}$ is mean of all satellite value and $\bar{P}_{obs}$ is mean of all rain gauge. The range is 1 that indicate perfect positive correlation to -1 that indicate perfect inverse correlation, with 0 as no linear correlation.

(d) False Alarm Ratio (FAR)

In the satellite rainfall context, the false alarm ratio measures the frequency of false alarms out of all the times rainfall event was predicted by the satellite. In brief, it was the ratio between the false alarm frequency over the total number of forecasted rain events by the satellite. The lower the FAR values, the better the satellite performance. The standard equation is shown in equation 4.

$$FAR = \frac{\text{False Alarm}}{\text{Hits} + \text{False Alarm}} \quad \text{Eqn.(4)}$$

where "False Alarms" are instances where the satellite detected rain but gauges did not and Hits is where both satellite and rain gauge were detecting rainfall. Lower FAR values signified good rainfall detections by the satellite and vice versa. It ranges between 0 and 1 with lower FAR indicate better detection ability.

(e) Probability of Detection (POD)

Probability of detection (POD) is an evaluation metric that quantify how effective the satellite precipitation correctly predicts the observed actual rainfall events on the ground. It is normally calculated by first identifying the rain events on the ground, and subsequently obtained the satellite precipitation at identical timing. Then, the number of hit cases between both is divided with the total cases. The value will be from 0-1 whereas values reaching 1 indicating perfect detection of POD. POD measures how well the satellite detect actual rainfall events observed by the ground rain gauges.

It ranges between 0 and 1 with higher POD indicate better detection ability. Equation 5 expressed the computation.

$$POD = \frac{\text{Hits}}{\text{Hits} + \text{Miss}} \quad \text{Eqn. (5)}$$

where Hits is where both satellite both satellite and rain gauge were detecting rainfall, Miss is where satellite did not detect the rainfall event identified by the rain gauge.

(f) Nash Sutcliffe Efficiency Index (NSE)

This NSE evaluate the predictive skill of the rain gauge compared to the satellite predictions. It was computed by dividing the sum of the product over all samples with the average deviation of the rain gauge and its mean. This index is widely used in hydrology modeling and since rainfall is part of the environmental hydrology as well, opting for this index could provide alternative performance of the satellite precipitation data. The values ranging from -1 to 1, and 1 indicating that the satellite had high efficiency to represent the rain at ground. Values reaching -1 indicating that the satellite precipitation efficiency is low. The standard equation for computing NSE is shown below.

$$NSE = 1 - \frac{\sum_{t=1}^{t} (RG_o - S_o)^2}{\sum_{t=1}^{t} (RG_o - RG_m)^2} \quad \text{Eqn. (6)}$$

where, RGo = rain gauge measurement at time t, So = satellite estimated rainfall value at time t, RGm = mean of rain gauge over the entire time period, T = total number of observations (time steps).

*Phase 3: Developing the scheme for reclassification mesoscale & synoptic rainfall at sub-daily scale*

The third phase of the proposed framework involved with designing the profiling scheme of the mesoscale and synoptic scale rainfall using the sub-daily products generated in the first phase. Because rainfall changes spatial pattern and intensity over space and time, it is a necessity to fix the temporal scale of the rain events. By screening all the rainy days samples of the various sub-daily products, their distribution, proportion, and percentile rain events will be determined via quantile classification. The dominant class will undergo detail classification using the Jenks Natural Break approach. This has been a widely used technique in effectively portray the distribution (Panek et al. 2019).

Subsequently, the pixel belongs to each significant classes or called rain pixel group (RPG) will be determined their respective spatial coverage. This is to determine whether they are belonging to which spatial category. This is done by applying the clustering analysis. Widely and practical algorithm including ISODATA can be suitable due to its effective and robustness (Teeparthi et al., 2021). The output of this process will inform us about the statistics of the most

common and dominant spatial rainfall patterns and its respective duration.

The next step of this profiling scheme is to determine the intensity of each RPG that already defined their spatial coverage which also will be known as RPG-S. To perform this, the kernel analysis will be executed. The average rainfall intensity over the entire event duration for all RPG-S will be computed. This process will produced information containing individual RPG-S (rain pixel group + spatial coverage) with their respective rainfall intensity or known as RPG-SI (rain pixel group + spatial coverage + intensity). The following step is to segregate and sort the significant RPG-SI and label them. The uncommon group can be secluded. In naming the RPG-SI, it is proposed to follow the sequence of duration, spatial coverage and intensity. Because there are many types of duration, spatial coverage and intensity, utilizing increasing integer representing the increasing values is recommended, for instance, if there are a class of RPG-SI that having 3.5hour duration (medium lived precipitation), spatial coverage of 12km (mesoscale, 4-100km), and intensity of 5.2mm/hr (medium rainfall), then the corresponding class name can be ML-MS02-I02.

*Phase 4: Implementation of the scheme and testing*

The final phase of the framework is to implement the scheme using the actual satellite precipitation dataset and summarizing the results. The execution of the reclassification scheme requires the usage of significant samples of dataset, which is in this context suggested to be not less than 90 days. This is due to the seasonal cycle of each monsoon season at humid tropics is approximately ranging up to 3 months. During this period, significant rainfall pattern was presence because of the seasonal flows that bring external front cloud to the equatorial regions.

Taking into consideration the high temporal of the satellite precipitation data (15 minutes), it means at daily basis it would be 96 images, and for the 90 days period could be consists of minimum of 8640 images. Performing the task by automated or semi-automated processing is highly recommended and using the high-performance computer. Cascading processing especially in the first and third phase can be executed seamlessly. Wu et al. (2018) had highlighted the appropriate requirement and specification of the high-performance computer for large data processing.

The output upon the completion of the scheme then will be performed cross tabulation analysis; to determine which classes that is majorly significant in term of frequency, or intensity. While it is expected that short lived to medium lived precipitation would be dominant due to the nature of rainfall in equatorial and maritime tropics, its distribution of intensity and spatial coverage might be varied. An intensive report consisting the statistics of that reclassification is useful for many respective applications that is related to hydro-environment issues such as climate change, disaster, and even public health.

## 4.0 Conclusion

This paper has presented the reclassification scheme of tropical rainfall using the Feng Yun satellite images for mesoscale and synoptic scale rainfall. It aims to improve the existing rainfall classification with the standard one that incorporates the three major elements; (1) duration, (2) spatial extent, and (3) duration. The proposed scheme is expected to be useful in making accurate and meaningful rainfall classification, but yet impactful for the responsible authorities as well as to the academic communities.

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