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STUDY OF THE EFFECTIVENESS OF COMMONLY USED RAINFALL MEASURING INSTRUMENTS IN MEASURING RAINFALL INTENSITY IN MALAYSIA

BY

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ABSTRACT

A study on the performance comparison in measuring the rainfall between three instruments and the tipping bucket rain gauge as a reference has been carried out and presented in this report. The three instruments are OTT PARSIVEL disdrometer, Theis Laser Disdrometer (Theis) and Vaisala Weather Transmitter (VXT). Seven months parallel rainfall measurement were conducted at five locations which spreaded out across Peninsular Malaysia. Data with missing values more than 5% of the total data will be excluded from further analysis. In general, during the heavy rainfall events, Theis recorded relatively higher rainfall amount and intensity compared to the other instruments. OTT and VXT presented a better agreement to those rainfall amount and intensity measured by tipping bucket. Generally, instruments with higher resolution such as OTT, Thies and VXT are able to measure lighter rainfall events with amount less than 0.2 mm/min and able to measure higher rainfall duration with respect to reference tipping bucket rain gauge. Overall, the result from Melaka station has shown that OTT are the most sensitive to light rainfall, followed by Theis and VXT. VXT presented the closer match the reference tipping bucket measurement. The tipping bucket that currently being used is reliable especially for operational purpose and climate study.

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1.0 INTRODUCTION

1.1 Background Study

One of the toughest challenges in meteorology is to measure the rainfall due to its extreme spatial, temporal and intensity variability (Lanza et al. 2010; Wang et al. 2008). Measurement at a one-minute time scale is very important for impact mitigation, especially within the urban environment due to extreme rainfall intensity variability that could cost lives, distructions of property and infrastructures during intense events (Lanza et al. 2010). It is crucial for rainfall intensity data to be generated from commonly used rainfall measuring instruments to provide a better understanding of this element as well as the development of calibration methods for impact based sensors. According to Tokay et al. (2003) and Molini et al. (2005), it has been a tropical issue in meteorology and hydrology on the accuracy of the rainfall intensity measurements acquired from rain gauges and their compared performance. World Meterological Organization (WMO) defined precipitation intensity as the amount of precipitation, collected per unit time interval (WMO, 2006).

There are various types of instruments available to measure rainfall, from the conventional rain gauge that can only measure the rainfall intensity and duration, to more developed instruments that applied optical and electronic techniques, which can measure the size, shape and velocity of rainfall particles (Liu et al. 2013). Tipping bucket rain gauges are often used for operational and experimental ground-based rainfall measurements by various national weather agencies, including Malaysia Meteorological Department (MMD). As explain in Wang et al. (2008), this mechanical device measure rainfall directly in increment of 0.254 mm, or one tip at a discrete point location on the earth’s surface. Currently, there are 43 main meteorological stations across Malaysia that are equipped with tipping bucket rain gauge. This device has been used by MMD since 1996. However, it is well known that measurement of rainfall intensity at the ground is commonly affected by both random and systemic errors (e.g., Mekonnen et al. 2015; Servuk 1982). Errors related to splashing, wetting and evaporation processes, due to weather conditions at the collector are known as catching errors. Despite experiencing errors, according to WMO Laboratory Intercomparison report (Lanza et al. 2006), tipping bucket applied with proper correction software is considered comply with the WMO specifications on the required accuracy for rainfall intensity measurements.

At present, some of the MMD stations are also equipped with other rainfall intensity measurement instruments such as OTT PARSIVEL disdrometer (OTT), Theis Laser Disdrometer (Theis) and Vaisala Weather Transmitter (VXT) for research purposes. Besides measuring the rainfall amount, these instruments are capable to measure the precipitation intensity, velocity, shape and drop size distributions. In addition, these instruments are also widely used disdrometer for rainfall measurement comparison and weather radar validations (Kathiravelu 2016; Liu et al. 2013; Thurai et al. 2010; Wong 2012). According to Liu et al. (2013), although comparison has been done to verify the accuracy of disdrometer in rainfall measurement, there is still no reference instrument that can obtain the true values. Few studies showed that different instruments depicted different discrepancies in measuring rainfall (etc, Liu et al. 2013; Löhnert et al. 2011). Therefore, this has motivated us to conduct a study on the effectiveness of commonly used rainfall measuring instruments in measuring rainfall intensity in Malaysia. In this study, data recorded by tipping bucket were used as the reference for comparison and accessing the performance of OTT, Theis and VXT in recording the rainfall amount in Malaysia.

1.2 Objectives

The objectives of the study are:-

i. To analyse rainfall intensity data between reference distrometer and tipping bucket rain gauge.

ii. To retrieve different rainfall intensity data based on different rainfall characteristics due to monsoonal influences.

iii. To derive a suitable relationship for rainfall intensity between the reference distrometer and the tipping bucket rain gauge.

2.0 LITERATURE REVIEW

2.1 Rainfall Measuring Instruments

i. Tipping Bucket Rain Gauges

Tipping bucket Rain Gauge (TBRG) utilized in this study is RIMCO7499, a syphon-controlled tipping bucket, which is designed for long-term operation with minimal maintenance under all climatic conditions. The gold plated TBRG is made from corrosion resistance materials. Rain falling in the collecting area are directed through a syphon control unit and discharges as a steady stream into two compartment bucket mounted in unstable equilibrium. As each compartment is filled with rainfall volume 0.2 mm, the bucket will tilt alternately about its axis. Mechanical correction is applied to the raw measurement. The maximum range for the measurement between 2 and 400 mm/hr is ±5%, which fall within the error range recommended by WMO (±5%).

Table 2.1. Specification of tipping bucket rain gauge.

Collecting area	203 ± 0.2 mm
Resolution	0.2 mm. (capacity of one tip of the bucket)
Range of measurement	0-500 mm/h
Accuracy	± 5% for 2-400 mm/h

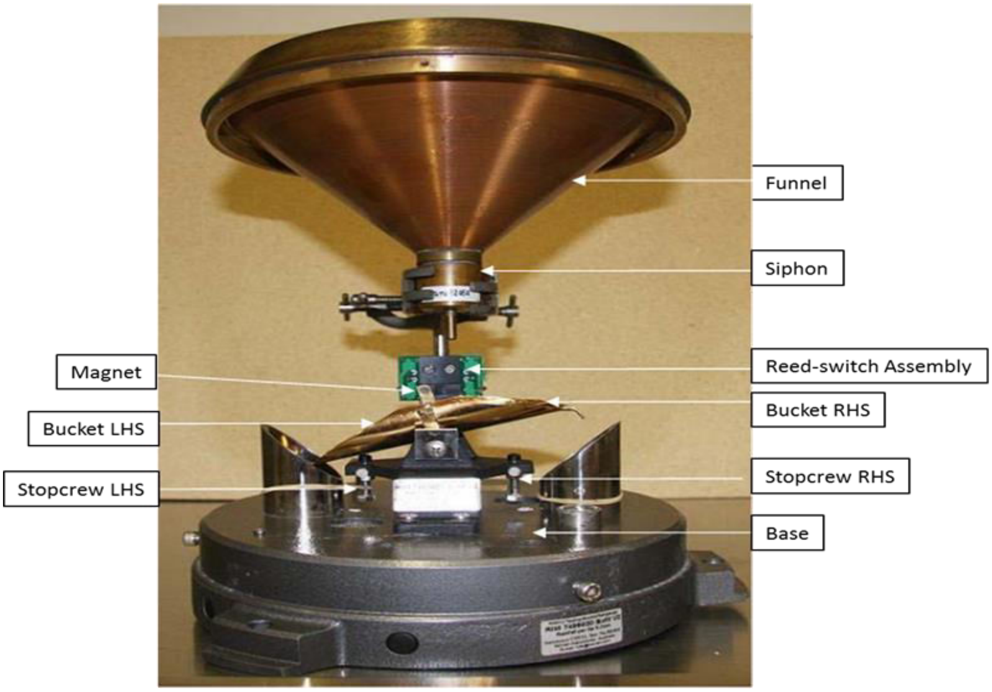


Figure 2.1. Rimco 7499 tipping bucket rain gauge

ii. OTT Parsivel Present Weather Sensor

The laser instruments have been widely use in rainfall studies are referred as disdrometer, optical spectropluviometer, or laser precipitation monitor, depending on the studies and application. One of the instruments is OTT Parsivel Present Weather Sensor, hereafter OTT, uses the light beam for precipitation monitoring. The optical laser diode wavelength used is 780 nm and the measuring area of the laser beam is 54 cm^2 (180 mm long, 30 mm wide). The precipitation information is determined from the size and velocity distribution information of hydrometeors over the measurement period. The hydrometeor is determined by measuring the light extinction when the hydrometeor falling through the light sheet of the sensors and will be categorized into 32 classes according to the size and velocity. Table below presents the technical specification of OTT quoted by the manufacturer.

Table 2.2. Specification of OTT Parsivel Present Weather Sensor

Collecting area	54 cm^2 (180mm long and 30 mm wide)
Measuring range	
Particle size for liquid precipitation	0.2 – 5 mm
Particle size for liquid precipitation	0.2 – 25 mm
Particle speed	0.2 – 20 m/s
Design	32 precipitation size classes 32 particle speed classes
Range of measurement	0.001 (drizzle rain) – 1,200 mm/h
Accuracy	± 5% for liquid precipitation ± 20% for solid precipitation

Figure 2.2. OTT Parsivel Laser Weather Sensor

iii. Thies Clima Laser Precipitation Monitor

Another laser-based instrument used in this study is the Thies Clima Laser Precipitation Monitor, hereafter Thies, manufactured by Adolf Thies GmbH & Co. KG at Göttinge, Germany. The principle used in LPM is similar to laser particle measuring system but with a simpler in design. It is a contactless measurement, hence it is not affected by other errors faced by the catching type rain gauges, such as evaporation losses and water retention in the funnel. The laser diode wavelength transmitted is 785 nm and the sensing area is about 40-47 cm^2. The diameter of raindrops pass through the laser beam is calculated from the amplitude of reduced transmitted signal and the fall velocity is estimated from the duration of reduced transmitted signal. LPM able to detect particle size ranges from 0.16 mm to more than 8mm and estimates particle speed from 0.2 to 20 m/s. The disdrometer computed the precipitation intensity by integrating the volumes of each droplet detected for every past minute. (Lazinger et al, 2006). Lanzinger et al. also proved that Thies has a low sensitivity level, as low as 0.2 mm/day, and having the ability to measure consistent and plausible values for the very light rainfall events.

Table 2.3. Specification of Thies Clima Laser Precipitation Monitor

Collecting area	40-47 cm^2 (instrument specific)
Particle size	0.16 - > 8 mm (for liquid and solid precipitation)
Particle speed	0.2 – 20 m/s
Range of measurement	0.005 - >250 mm/h
Accuracy **(wind speed < 3 m/s)**	≤ 15% for rain 0.5 – 20 mm/h ≤ 30% for snow
Disdrometer classes	440 classes (22 particle diameters × 20 particle speed)

Figure 2.3. The Thies Laser Precipitation Monitor. The square box contains the laser diode and all electronic components, while the receiver is mounted in a small enclosure opposite to it.

iv. Vaisala Weather Transmitter (VXT)

Vaisala weather transmitter is a compact weather instrument to measure various meteorological atmospheric elements, which include air temperature, relative humidity, wind speed and direction, pressure and rainfall. The instrument manufactured by Vaisala Inc, requires little maintenance upon deployment and minimal power usage during data collection. The rainfall sensor mounted in the instrument is referred as the RAINCAP sensor, which utilizes acoustic rain impact technology to derive rainfall information. Basara et al. (2009) quoted that the rainfall accumulation is measured as a function of the voltage signal of the hydrometeors as the impact the sensor. Each voltage signal is proportional to the volume of the specific hydrometeor which is then converted to accumulated rainfall. Below is the brief specification of the RAINCAP sensor in Vaisala Weather Transmitter (Vaisala, 2016).

Table 2.4. Specification of RAINCAP in Vaisala Weather Transmitter

Collecting area	60 cm^2
Output resolution	0.01 mm
Field accuracy for long-term accumulation	Better than 5 %, weather dependent
Rain duration	Counting each 10-second increment whenever droplet detected
Output resolution	10 s
Rain intensity	Running one minute average in 10 second steps.
Range	0 ... 200 mm/h (broader range with reduced accuracy)

Figure 2.4. Vaisala Weather Transmitter WXT520

2.2 Overview on Malaysia Rainfall

Malaysia is situated in the western part of the Maritime Continent, which known to have a very complicated land mass and topography. Malaysia's climate is categorized as equatorial, which is hot and humid throughout the year. The annual rainfall amount received is around 2000 mm - 3000 mm and its distribution is uneven from month to month and from one location to another. Generally, Malaysia's climate and weather are largely influenced by two types of major monsoon which are the southwest monsoon (June-July-August) and northeast monsoon (December-January-Febuary), and another two inter-monsoon seasons (Mac-April-Mei and September-October-November) (MMD website, 2016).

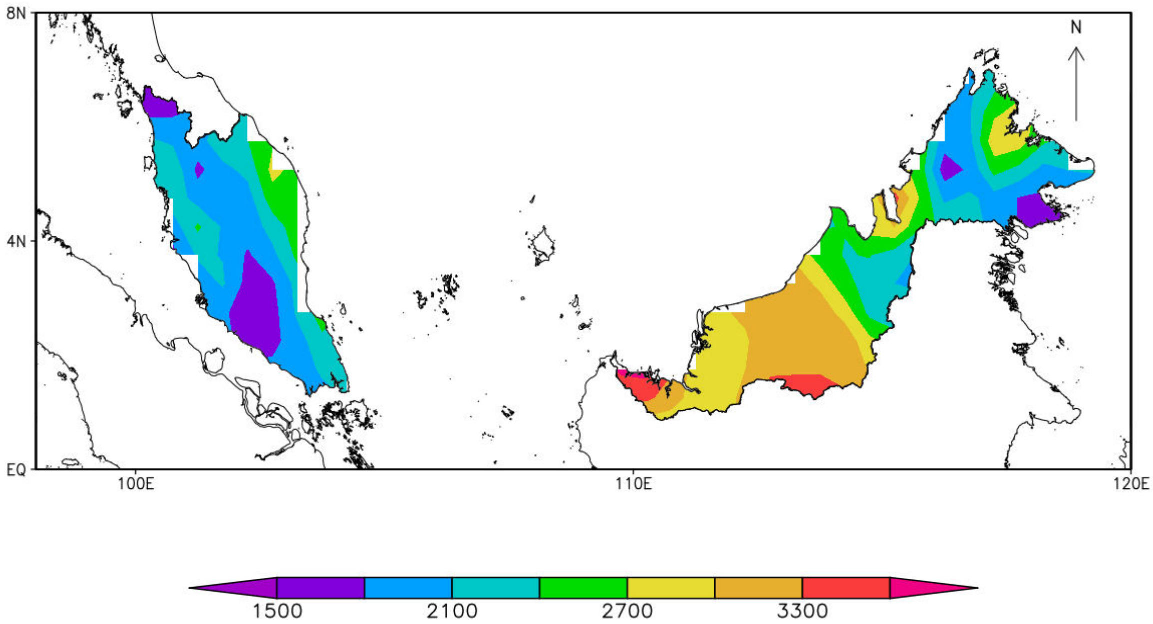


Figure 2.5. Spatial distribution of annual rainfall amount in Malaysia.

As shown in Figure 2.5, generally Malaysia receives most of its annual rainfall during northeast monsoon, especially over the east coast of Peninsular Malaysia, which is facing the South China Sea. On the other hand, the west coast of Peninsular Malaysia receives the least annual rainfall especially during the southwest monsoon due to its location, which blocks by

Sumatra. However, during the inter monsoon seasons, this area receives surplus amount of rainfall due to orographic effects. The same goes to some part of Sabah state, which also blocked by the Crocker mountain range. Overall, east Malaysia experiencing more and even rainfall compared to that of Peninsular Malaysia. The highest annual rainfall amount is observed in Kuching with more than 3600mm (Figure 2.5).

In larger scale, Malaysia rainfall is influenced by the inter-annual variability phenomenon such as the El Niño. El Niño is a naturally occurring phenomenon in the Pacific Ocean that happens in 2 to 7 year cycle. According to Salimun et al. (2014), there are two different types of El Niños (conventional El Niño and El Niño Modoki), that give distinct impacts on Malaysia rainfall distribution especially during the boreal winter. During the conventional El Niño, significant negative impacts generally occurred over the northern Borneo while, during the El Niño Modoki, both Peninsular and east Malaysia experienced significant drier than normal conditions. During the strong 1997/1998 El Niño, Malaysia experienced severe drought especially over the northern part of Borneo and haze episode (Tangang et al. 2010), which led to health problems, closing of schools and other distructions.

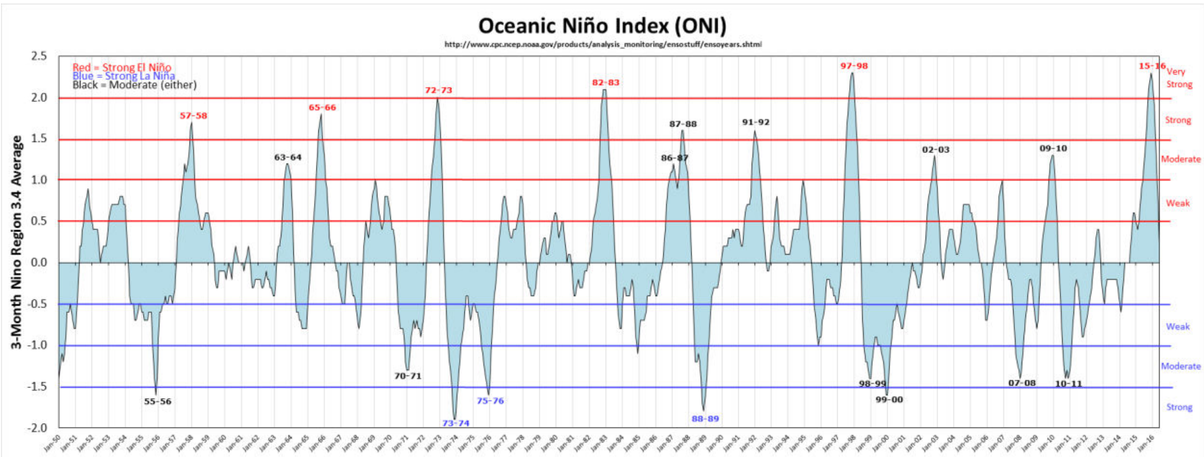


Figure 2.6. The Oceanic Niño index (ONI) from January 1950 to January 2015. Source: Climate Prediction Center (CPC).(http://www.cpc.noaa.gov)

Based on Figure 2.6, in 2015/2016 there is another very strong El Niño phenomenon occurred and the strength is comparable with the 1997/1998 event. Prof. Dr. Fredolin of University Kebangsaan Malaysia, former vice chairman of Working Group I at the

Intergovernmental Panel of Climate Change (IPCC), commented to the local news paper saying that this phenomenon is the strongest of the 20 over the last 60 years, but he did not link its heat intensity to global warming. MMD official website also reported that this El Niño episode influenced Malaysia rainfall variability. Since the end of year 2015, Malaysia experiencing higher temperature and dryer weather, and most of the stations across the country received less amount of rainfall until April 2015 especially in Sabah. However, it is astonishing that during January to March, while other areas received less rainfall, Sarawak received large amount of rainfall that led to severe flooding.

3.0 DATA AND METHODOLOGY

3.1 Study Locations

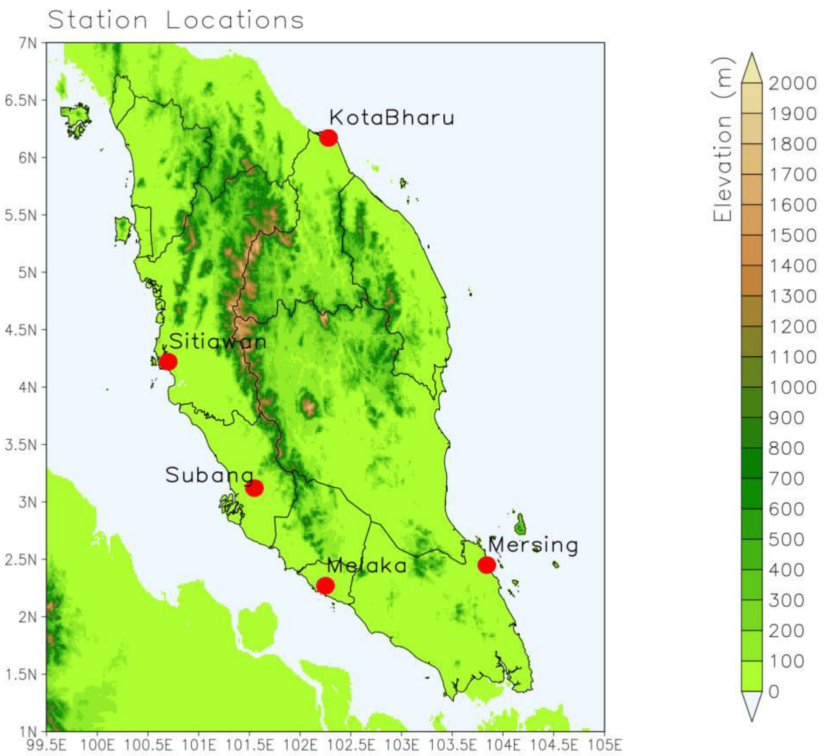


Figure 3.1. Location of the 5 meteorological stations considered in this study.

Five different meteorological ground-based stations spreading across the Peninsular of Malaysia heve been chosen for this study. These meteorological stations are Kota Bharu, Sitiawan, Subang, Melaka and Mersing, which are located at the state of Kelantan, Perak, Selangor, Melaka and Pahang, respectively. The locations of those chosen meteorological ground-based stations were listed in Figure 3.1. These stations were spreaded out at the east-west coast of the Peninsular Malaysia to cater for the different monsoon regimes which dominate the east and west coast of Peninsular Malaysia depending on the monsoon season. Also, these 5 stations have rainfall record for at least 10 years (from 2003 till 2013) are shown in the **Appendix A.**

3.1.1 Dataset

This study examined the rainfall data from January 2016 to July 2016 collected by 5 different meteorological ground-based stations spreading across the Peninsular of Malaysia using various instruments available to each station. These instruments are, tipping bucket, OTT Laser Distrometer (OTT), Theis Laser Distrometer (Thies) and Vaisala Weather Transmitter (VXT). The list of the stations used and the type of instruments available for each respective station were given in Table 3.1 and can be found in the **Appendix B**. The temporal resolution of these data is one minute. The data recorded by tipping bucket was used as the reference data for comparison and accessing the performance of OTT, Theis and VXT in recording the rainfall data.

Table 3.1. List of stations used and types of instrument available at each respective station.

Station Location	Latitude	Longitude	Instruments Availbility			
			Tipping Bucket	Thies Laser Disdrometer (Thies)	OTT Laser Disdrometer (OTT)	Vaisala Weather Transmitter (VXT)
KotaBharu	6.17° N	102.28° E	√		√	√
Sitiawan	4.22° N	100.70° E	√		√	
Subang	3.12° N	101.55° E	√	√		
Melaka	2.27° N	102.25° E	√	√	√	√
Mersing	2.45° N	103.84° E	√	√		

3.2 Data processing and analysis

Prior to analysis, the number of missing data per month of each of the rainfall event needs to be identified. Following the approach of Juneng et al. (2009), the record with missing data of 5% or more will be discarded without further action. Descriptive statistics of mean daily total, maximum daily total, monthly total rainfall amount and duration were calculated using the Mircosoft Excel software in order to obtain a general picture of the rainfall behavior over each of the stations chosen at each particular month, which will be discussed in next section.

The agreement between the rainfall amount and duration observed by Thies, OTT and VXT were compared against that of tipping bucket using the statistical package in MATLAB software developed by MathWorks. Instrument Thies, OTT and VXT at each station, which unable to record rainfall data accurately, with respect to the tipping bucket were dropped from further analysis. A frequency distribution function was constructed using the statistical package from the MATLAB software developed by MathWorks for each of the rainfall data observed by tipping bucket, Thies, OTT and VXT in order to understand the behavior of the instruments. Differences between the rainfall data at daily time scale observed by tipping bucket and Thies, OTT and VXT are calculated using the Climate Data Operators (CDO) software developed by the Max-Planck Institute. These differences provide a benchmark on the performance of Thies, OTT and VXT in recording the rainfall data with respect to tipping bucket. Rainfall intensity were calculated from the tipping bucket data and were then compared with that of Thies, OTT and VXT in order to assess the ability of sensors in measuring the rainfall intensity using CDO as well.

The flow of the analysis is summarized in the flow-chart below:

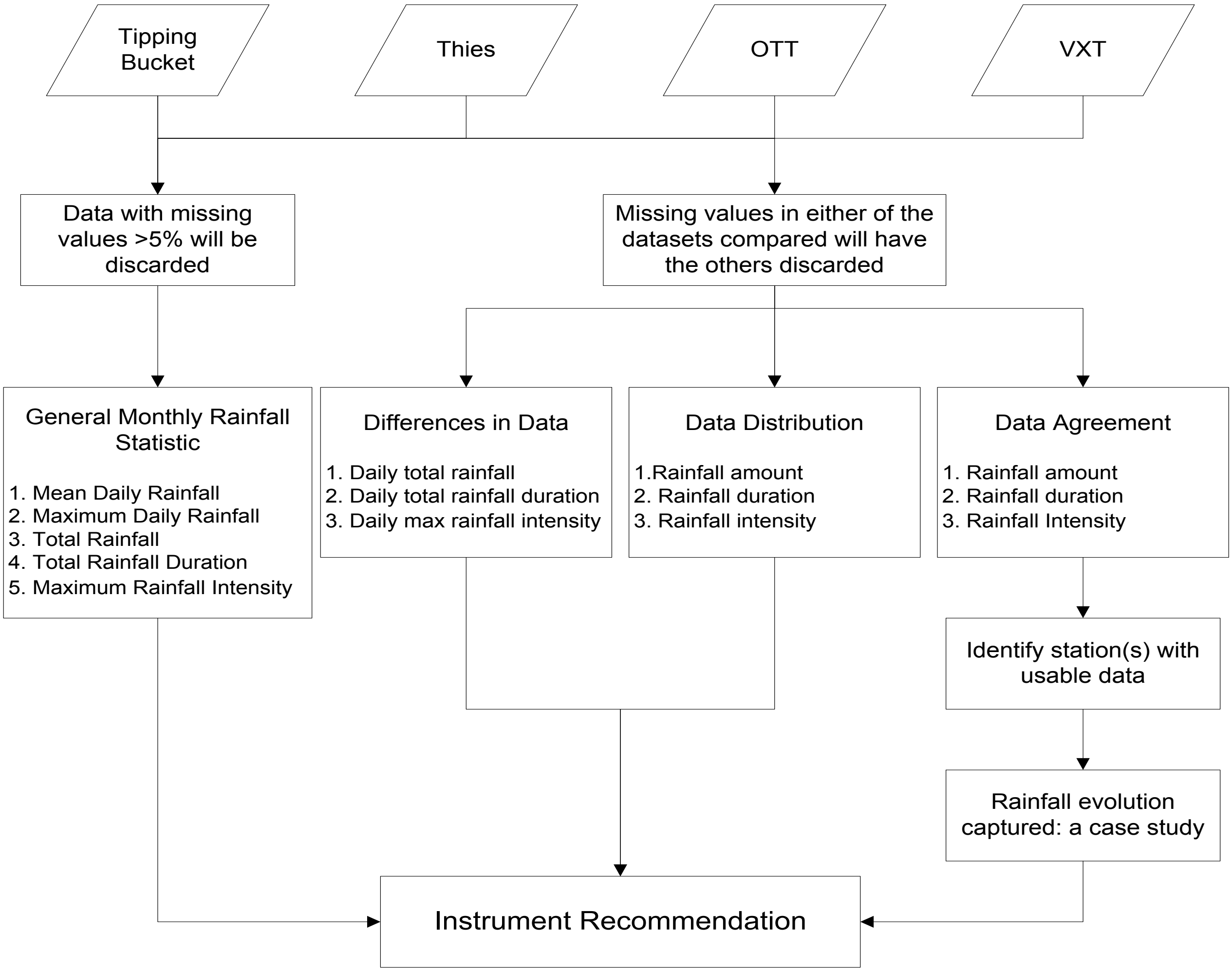


Figure 3.2. Analysis flow-chart

3.0 RESULT AND DISCUSSION

The primary objective of the study is to assess the differences in rainfall intensity between tipping bucket and new sensors, a series of comparison for all the stations will be shown for parameters, such as rainfall amount, duration and intensity over the 7 months period, starting from 1st January to 31st July 2016.

Prior to the comparison analysis, the percentage of missing data found in every month in each sensor for all station were computed and shown in the Table 4.1. Most of the instruments give a very high percentage of data return with few exceptions, which are shown in Table 4.1 with bolded values. Station Melaka, which consists of four different sensors installed in the station, showed an overall high percentage data records except for data recorded by Thies and VXT in June. Both of the sensors gave percentage of missing data about 7-7.5% in that particular month. Missing data found in Mersing is relatively much higher than other station and sensors, it yields more than 50% of the total data recorded for parameters measured by Thies in January, February and June. Both the OTT in Sitiawan and Thies in Subang recorded percentages of missing data ~20% and ~23%, respectively in January. In overall, tipping bucket rain gauges used in all station giving a great percentage of data return with missing data less than 5% of total data recorded in all month. Note that months with missing more than 5% in that particular will be excluded in the subsequent basic statistical analysis. However, it will still be used in the subsequent comparison analysis between sensors.

For general comparison purposes, basic statistical analysis of rainfall, such as mean daily total rainfall, maximum daily total rainfall, total rainfall and duration, and maximum rainfall intensity was conducted from the six months of parallel rainfall measurement at each station and displayed in Table 4.2 to 4.6. The percentage of differences between tipping bucket and each sensor (tipping bucket - sensor) were also computed and shown in these tables.

In Table 4.2, Kota Bahru recorded the highest rainfall measurement in June and July with the total rainfall more than 170 mm in both months. April recorded the lowest rainfall measurement with total rainfall less than 1 mm. OTT measurements gave all zero values with almost full data return in January. The average daily total rainfall range between 0 – 6 mm/day and 3.1 – 66.1 mm/day for tipping bucket and OTT, respectively, whereas the total duration recorded in a month are range between 2 – 359 minutes for tipping bucket and 519 – 3911 minutes for OTT. The rainfall measured by tipping bucket in Kota Bahru are overall much more lower compared to rainfall recorded by OTT, especially in April and June. The total rainfall duration recorded by tipping bucket in the 7-month period is 1201 minutes, which is only ~1/10 of the total rainfall duration recorded by OTT.

The wettest period in Melaka occurred during May-June and driest during March. This feature is well measured by all the sensors in Melaka especially during the dry period (Table 4.3 and 4.4), with total rainfall in March range between 6.8 (tipping bucket) to 15.4 (VXT) across sensors. VXT recorded the wettest month in July instead of May-June, as measured by other sensors. We would expect that Thies and VXT recorded the highest total rainfall in June if the missing data in this particular month are sufficient for this analysis.

Mean daily total rainfall, maximum daily rainfall, total rainfall and maximum rainfall intensity recorded by OTT and tipping bucket in January to March at Melaka were in good agreement with differences fall within and close to ±10. Absolute differences in these parameters increase starting from April where the weather becoming wetter and peaked to ~30% in the wettest month, June. OTT overestimated the rainfall during the driest and wettest months, and underestimates in the other months. The maximum intensity estimated by OTT in June is enormously large, which is three to four folds of the maximum intensity estimated from tipping bucket. The total rainfall duration recorded by OTT ranged between 113 – 1662 minutes, while tipping bucket ranged between 18 – 584 minutes. Total rainfall duration of OTT are always higher than those recorded by tipping bucket. Overall, along the 7-month measurement period, mean daily rainfall, maximum daily rainfall and total rainfall measured by OTT is lower than those measured by tipping bucket with differences less than 15% (Table 4.4). Overall maximum intensity measured by both sensors are in good agreement to each other. It is make sense than the total duration of OTT is much higher than tipping bucket due to the low resolution of tipping bucket rain gauge.

Mean daily total rainfall, maximum daily rainfall and total rainfall measured by VXT were lower than those measured by tipping bucket in most months except the drier month, March and April, where the rainfall measured are higher than rainfall measurement from tipping bucket. Measurement in July shows the best agreement in both sensor with the differences in all parameters fall within ±10%. Total rainfall duration recorded in VXT were higher in most months except January and May. Overall, the VXT measured lower rainfall than tipping bucket, as shown in Table 4.4 with highest difference found in maximum rainfall intensity and lowest in total rainfall duration along the 7-month measurement campaign. All of rainfall parameters measured by Thies were higher than those measured by tipping bucket with differences more than 65% except 46.9% for mean daily total rainfall and total rainfall in January and 23.6% for total rainfall duration in May.

No statistics available for Thies measurement in January, February and June at Mersing station due to the large amount of missing data in the observation (Table 4.1 and 4.5). Based on the tipping bucket measurement, the wettest month in Mersing was occurred in June, with total rainfall 120 mm (Table 4.5) and followed by February (total rainfall 104 mm). The least rainfall recorded by both sensors was in April with total rainfall 2.8 mm for tipping bucket and 7.4 mm for Thies. Similar to the rainfall measurement made by Thies in Melaka, rainfall recorded by Thies were always higher than those recorded by tipping bucket in Mersing. The discrepancies in all rainfall parameters were higher than 70%.

Table 4.6 depicts the basic statistic for rainfall measurement made by tipping bucket and OTT for Station Sitiawan. No statistics has been done to rainfall data from OTT due to large amount of missing data. Rainfall recorded July as the wettest month and April as the driest month in both for both sensors in Sitiawan. From February to July, total rainfall ranged between 38 – 203 mm for tipping bucket with average 111 mm and 49 – 161 mm for OTT measurement with average slightly lower (~13%) than tipping bucket, that is 96.2 mm. Mean daily rainfall maximum daily rainfall and total rainfall in March showed a very good agreement between both sensors, that is within the absolute differences less than 3% for March and 10% for June. Maximum rainfall intensity estimated by both sensors are agreed well to each other with the absolute differences fall within 10%. The overall difference in maximum intensity between both sensors are relatively small, ~4% higher for OTT with respect to tipping bucket. Similar to the total rainfall duration measurement made by other sensors, total duration measured by OTT is much higher with respect to total duration of tipping bucket in Sitiawan. Discrepancies significantly increase in wetter month, July. Mean daily total rainfall and total rainfall reach difference of ~21% and up to 34% for maximum daily rainfall. Overall, measurement made by OTT is agree reasonably well with the measurement made by tipping bucket in Sitiawan Station.

Table 4.7 depicts the basic statistics for rainfall measurement made by tipping bucket and Thies for Station Subang. No statistics has been done to rainfall data from Thies due to large amount of missing data. In Subang, the wettest month occurred in May and driest month in February for both sensors, which is very different from other stations. During the period February to July, total rainfall ranged between 71 – 369 mm for tipping bucket with average 207 mm and 91 – 580 mm for Thies measurement with average much lower (~58%) than tipping bucket, that is 328 mm. The most intense rainfall was both occurred in May with maximum intensity 215 mm/hr for tipping bucket and 485 mm/hr for Thies. Overall, measurement made by Thies is much higher than the measurement made by tipping bucket in Subang Station.

From the basic statistical analysis for January to July for these five stations selected, the relatively small discrepancies found between OTT and tipping bucket (Melaka and Sitiawan) and between VXT and tipping (Melaka) suggest that OTT and VXT are able to measured rainfall closer to rainfall measurement from tipping bucket. OTT measurement in Kota Bahru station gave an enormously large rainfall amount and it is suspected that disturbances or errors occurred during the measurement campaign. Thies measurement generally recorded higher rainfall than other sensors. This basic statistics results give us an overview on the general rainfall pattern measured by sensors involved along the measurement campaign. However, these is not sufficient to investigate the difference rainfall characteristics derived from different sensor and establish the relationship between each sensor and tipping bucket. Hence, more intensive comparison analysis were needed and are shown in the following section.

The differences between reference tipping bucket rain gauges and other sensors are further investigate by looking at the time series of daily rainfall parameters such as daily total rainfall amount, daily total rainfall duration and daily maximum rainfall intensity have been derived and plotted to show the day-to-day evolution of these rainfall parameters for the purpose of assessing the differences between the reference tipping bucket rain gauge and other sensors under different rainfall intensity.

Figure 4.1 – 4.3 depict the time series of derived daily total rainfall amount, daily total rainfall duration, daily maximum rainfall intensity and the percentage of difference between OTT and reference tipping bucket rain gauge for Kota Bahru Station along the 7-month rainfall measurement campaign. From those figures, we could see that OTT measured extraordinary high rainfall compared to tipping bucket rain gauge especially during the wetter month in June and the beginning of July (Figure 4.1(a), 4.2(a) and 4.3(a)). The daily total rainfall amount recorded by OTT could reach more than 330 mm/day and the percentage of difference are more 10000%.

By consolidating the result from Table 4.2 and Figure 4.1-4.3, we could conclude that OTT failed to capture the day-to-day evolution and basic characteristics of rainfall in Kota Bahru station. Huge differences existed between tipping bucket and OTT has motivated us to look into the output data produced by both instruments. Unfortunately, it was found that the sensor status for OTT is flagged as damage of laser sensor or the laser protective glass is dirty and partially covered in most of time of the measurement campaign Hence the subsequent data recorded are not recommended to be used in any further analysis as stated in the instrument manual. Eventually, with the large portion of data recorded were flagged and enormously huge differences found in the rainfall parameters recorded, Kota Bahru will be excluded from the subsequent comparison analysis. However, the comparison material between OTT and tipping bucket can be found in the **Appendix C**.

Table 4.1. Percentage of missing data for every month recorded by each instrument at all stations. Values in bold represent precentage of missing data recorded more that 5% of the total data recorded in its respective month.

Instruments	Output parameters	Percentage of Missing Data per Month (%)						
		Jan	Feb	Mar	Apr	May	Jun	July
Station Kota Bahru								
Tipping Bucket	Amount	0.13	0.01	0.33	4.2	3.28	3.45	3.37
OTT Laser Disdrometer	Amount	0.01	0.02	0.07	0.13	0.3	4.08	0.51
	Intensity	0.01	0.01	0.05	0.1	0.26	3.98	0.41
Station Melaka								
Tipping Bucket	Amount	0.13	1.14	0	3.19	3.23	3.33	3.23
OTT Laser Disdrometer	Amount	0.11	0.51	0.45	0.81	3.17	2.52	0.69
	Intensity	0.08	0.44	0.39	0.71	3.06	2.41	0.59
Thies Laser Disdrometer	Amount	2.05	0.78	0.93	1.1	3.51	**7.47**	0.99
	Intensity	1.87	0.69	0.84	0.98	3.4	**7.38**	0.89
Vaisala Weather Transmitter	Amount	0.07	0.42	0.39	0.68	3.03	**7.13**	0.57
	Intensity	0.07	0.42	0.39	0.68	3.03	**7.13**	0.57
Station Mersing								
Tipping Bucket	Amount	0.13	0.06	1.32	3.19	3.23	3.33	3.23
Thies Laser Disdrometer	Amount	**60.88**	**52.63**	4.49	4.05	0.12	**56.67**	0.10
	Intensity	**60.71**	**52.61**	4.44	4.04	0.11	**56.66**	0.09
Station Sitiawan								
Tipping Bucket	Amount	0.14	0	0	4.72	4.41	3.34	3.23
OTT Laser Disdrometer	Amount	**20.57**	4.02	3.86	0.83	1.35	0.47	0.54
	Intensity	**20.5**	3.95	3.81	0.75	1.26	0.42	0.45
Station Subang								
Tipping Bucket	Amount	0.16	0.04	0.08	3.27	4.2	3.35	3.23
Thies Laser Disdrometer	Amount	**23.19**	0.81	0	0.19	0.7	4.46	0.99
	Intensity	**23.1**	0.78	0	0.17	0.67	4.19	0.87

* Although the percentage of missing data is less than 5%, however, the rainfall parameters recorded were suspicious. Hence, it will dropped from the descriptive statistical analysis.

Table 4.2. Basic statistics for Station Kota Bahru.

Month	Rainfall Parameters	TBRG	OTT	Difference (%)
January	Mean Daily Total Rainfall (mm/day)	2.91	0.00	-100.0
	Maximum Daily Total Rainfall (mm/day)	51.00	0.00	-100.0
	Total Rainfall (mm)	90.20	0.00	-100.0
	Total Rainfall Duration (minutes)	189.00	0.00	-100.0
	Maximum Intensity (mm)	156.00	0.00	-100.0
February	Mean Daily Total Rainfall (mm/day)	3.25	6.03	85.5
	Maximum Daily Total Rainfall (mm/day)	30.20	121.71	303.0
	Total Rainfall (mm)	94.20	174.78	85.5
	Total Rainfall Duration (minutes)	232.00	519.00	123.7
	Maximum Intensity (mm)	132.00	639.04	384.1
March	Mean Daily Total Rainfall (mm/day)	0.93	3.06	229.0
	Maximum Daily Total Rainfall (mm/day)	20.40	11.04	-45.9
	Total Rainfall (mm)	28.80	94.79	229.1
	Total Rainfall Duration (minutes)	69.00	830.00	1102.9
	Maximum Intensity (mm)	84.00	441.98	426.2
April	Mean Daily Total Rainfall (mm/day)	0.01	6.30	62900.0
	Maximum Daily Total Rainfall (mm/day)	0.40	33.69	8322.5
	Total Rainfall (mm)	0.40	188.90	47125.0
	Total Rainfall Duration (minutes)	2.00	1203.00	60050.0
	Maximum Intensity (mm)	12.00	1104.91	9107.6
May	Mean Daily Total Rainfall (mm/day)	4.85	8.22	69.5
	Maximum Daily Total Rainfall (mm/day)	53.60	44.69	-16.6
	Total Rainfall (mm)	150.20	254.75	69.6
	Total Rainfall Duration (minutes)	260.00	1448.00	456.9
	Maximum Intensity (mm)	192.00	515.80	168.7
June	Mean Daily Total Rainfall (mm/day)	5.97	66.11	1007.4
	Maximum Daily Total Rainfall (mm/day)	48.20	193.77	302.0
	Total Rainfall (mm)	179.20	1983.18	1006.7
	Total Rainfall Duration (minutes)	359.00	3911.00	989.4
	Maximum Intensity (mm)	156.00	993.42	536.8
July	Mean Daily Total Rainfall (mm/day)	5.52	45.03	715.8
	Maximum Daily Total Rainfall (mm/day)	57.00	349.79	513.7
	Total Rainfall (mm)	171.20	1395.90	715.4
	Total Rainfall Duration (minutes)	279.00	2801.00	903.9
	Maximum Intensity (mm)	204.00	953.82	367.6
Overall	Mean Daily Total Rainfall (mm/day)	3.35	22.29	565.4
	Maximum Daily Total Rainfall (mm/day)	57.00	349.79	513.7
	Total Rainfall (mm)	714.20	4092.30	473.0
	Total Rainfall Duration (minutes)	1390.00	10712.00	670.65
	Maximum Intensity (mm)	204.00	1104.91	441.6

Table 4.3. Basic statistics for Station Melaka.

Month	Rainfall Parameters	TBRG	OTT	Difference (%)	Thies	Difference (%)	VXT	Difference (%)
January	Mean Daily Total Rainfall (mm/day)	4.93	4.98	1.0	7.24	46.9	4.28	-13.2
	Maximum Daily Total Rainfall (mm/day)	42.40	42.26	-0.3	90.84	114.2	37.00	-12.7
	Total Rainfall (mm)	152.80	154.51	1.1	224.40	46.9	132.80	-13.1
	Total Rainfall Duration (minutes)	415.00	1382.00	233.0	975.00	134.9	386.00	-7.0
	Maximum Intensity (mm)	120.00	121.06	0.9	885.00	637.5	99.30	-17.3
February	Mean Daily Total Rainfall (mm/day)	6.14	5.89	-4.1	10.73	74.8	5.71	-7.0
	Maximum Daily Total Rainfall (mm/day)	47.40	43.72	-7.8	78.58	65.8	41.30	-12.9
	Total Rainfall (mm)	178.20	170.71	-4.2	311.27	74.7	165.60	-7.1
	Total Rainfall Duration (minutes)	445.00	1156.00	159.8	1247.00	180.2	489.00	9.9
	Maximum Intensity (mm)	132.00	150.02	13.7	295.57	123.9	109.00	-17.4
March	Mean Daily Total Rainfall (mm/day)	0.22	0.24	9.1	0.39	77.3	0.50	127.3
	Maximum Daily Total Rainfall (mm/day)	4.80	4.90	2.1	8.00	66.7	7.30	52.1
	Total Rainfall (mm)	6.80	7.55	11.0	12.24	80.0	15.40	126.5
	Total Rainfall Duration (minutes)	18.00	113.00	527.8	149.00	727.8	79.00	338.9
	Maximum Intensity (mm)	48.00	50.60	5.4	87.48	82.3	70.30	46.5
April	Mean Daily Total Rainfall (mm/day)	3.72	3.03	-18.5	6.69	79.8	4.00	7.5
	Maximum Daily Total Rainfall (mm/day)	39.60	34.32	-13.3	78.65	98.6	45.60	15.2
	Total Rainfall (mm)	111.60	90.83	-18.6	200.76	79.9	119.90	7.4
	Total Rainfall Duration (minutes)	206.00	569.00	176.2	646.00	213.6	277.00	34.5
	Maximum Intensity (mm)	156.00	173.45	11.2	373.99	139.7	117.50	-24.7
May	Mean Daily Total Rainfall (mm/day)	6.74	5.07	-24.8	12.05	78.8	5.61	-16.8
	Maximum Daily Total Rainfall (mm/day)	65.40	46.75	-28.5	138.71	112.1	48.30	-26.1
	Total Rainfall (mm)	209.00	157.10	-24.8	373.48	78.7	174.00	-16.7
	Total Rainfall Duration (minutes)	437.00	1513.00	246.2	540.35	23.6	140.20	-67.9
	Maximum Intensity (mm)	156.00	151.64	-2.8	-	-	-	-

Table 4.4. Basic statistics for Station Melaka (continued).

Month	Rainfall Parameters	TBRG	OTT	Difference (%)	Thies	Difference (%)	VXT	Difference (%)
June	Mean Daily Total Rainfall (mm/day)	11.35	14.69	29.4	-	-	-	-
	Maximum Daily Total Rainfall (mm/day)	90.20	107.21	18.9	-	-	-	-
	Total Rainfall (mm)	340.40	440.81	29.5	-	-	-	-
	Total Rainfall Duration (minutes)	584.00	1662.00	184.6	-	-	-	-
	Maximum Intensity (mm)	120.00	552.79	360.7	-	-	-	-
July	Mean Daily Total Rainfall (mm/day)	6.49	5.78	-10.9	10.77	65.9	6.16	-5.1
	Maximum Daily Total Rainfall (mm/day)	49.00	40.40	-17.6	90.26	84.2	45.10	-8.0
	Total Rainfall (mm)	201.20	179.12	-11.0	333.90	66.0	190.90	-5.1
	Total Rainfall Duration (minutes)	488.00	1508.00	209.0	1621.00	232.2	524.00	7.4
	Maximum Intensity (mm)	132.00	114.07	-13.6	267.99	103.0	131.10	-0.7
Overall	Mean Daily Total Rainfall (mm/day)	5.66	5.67	-0.2	6.84	-20.9	3.75	33.8
	Maximum Daily Total Rainfall (mm/day)	90.20	107.21	-18.9	138.71	53.8	48.30	46.5
	Total Rainfall (mm)	1200.00	1200.63	-0.05	1456.05	-21.3	798.60	33.5
	Total Rainfall Duration (minutes)	2593.00	7903.00	204.8	5178.35	-99.7	1895.20	26.9
	Maximum Intensity (mm)	156.00	552.79	-254.35	885.00	467.3	131.10	-16.0

Table 4.5. Basic statistics for Station Mersing.

Month	Rainfall Parameters	TBRG	Thies	Difference (%)
January	Mean Daily Total Rainfall (mm/day)	1.91	-	-
	Maximum Daily Total Rainfall (mm/day)	33.00	-	-
	Total Rainfall (mm)	59.20	-	-
	Total Rainfall Duration (minutes)	160.00	-	-
	Maximum Intensity (mm)	132.00	-	-
February	Mean Daily Total Rainfall (mm/day)	3.61	-	-
	Maximum Daily Total Rainfall (mm/day)	30.40	-	-
	Total Rainfall (mm)	104.60	-	-
	Total Rainfall Duration (minutes)	309.00	-	-
	Maximum Intensity (mm)	96.00	-	-
March	Mean Daily Total Rainfall (mm/day)	0.27	0.42	55.6
	Maximum Daily Total Rainfall (mm/day)	4.40	5.80	31.8
	Total Rainfall (mm)	8.40	12.97	54.4
	Total Rainfall Duration (minutes)	37.00	245.00	562.2
	Maximum Intensity (mm)	36.00	26.99	-25.0
April	Mean Daily Total Rainfall (mm/day)	0.09	0.25	177.8
	Maximum Daily Total Rainfall (mm/day)	1.60	2.37	48.1
	Total Rainfall (mm)	2.80	7.42	165.0
	Total Rainfall Duration (minutes)	13.00	133.00	923.1
	Maximum Intensity (mm)	24.00	100.70	319.6
May	Mean Daily Total Rainfall (mm/day)	2.21	3.81	72.4
	Maximum Daily Total Rainfall (mm/day)	14.60	35.56	143.6
	Total Rainfall (mm)	68.40	118.16	72.7
	Total Rainfall Duration (minutes)	108.00	426.00	243.5
	Maximum Intensity (mm)	876.00	295.02	66.3
June	Mean Daily Total Rainfall (mm/day)	4.01	-	-
	Maximum Daily Total Rainfall (mm/day)	35.00	-	-
	Total Rainfall (mm)	120.40	-	-
	Total Rainfall Duration (minutes)	245.00	-	-
	Maximum Intensity (mm)	144.00	-	-
July	Mean Daily Total Rainfall (mm/day)	1.54	2.65	72.1
	Maximum Daily Total Rainfall (mm/day)	32.40	58.17	79.5
	Total Rainfall (mm)	47.60	82.17	72.6
	Total Rainfall Duration (minutes)	97.00	644.00	597.9
	Maximum Intensity (mm)	120.00	326.17	171.8
Overall	Mean Daily Total Rainfall (mm/day)	1.95	1.79	8.2
	Maximum Daily Total Rainfall (mm/day)	35.00	58.17	-66.2
	Total Rainfall (mm)	411.40	220.72	46.4
	Total Rainfall Duration (minutes)	969.00	1448.00	-49.6
	Maximum Intensity (mm)	876.00	326.17	62.77

Table 4.6. Basic statistics for Station Sitiawan.

Month	Rainfall Parameters	TBRG	OTT	Difference (%)
January	Mean Daily Total Rainfall (mm/day)	0.99	-	-
	Maximum Daily Total Rainfall (mm/day)	11.80	-	-
	Total Rainfall (mm)	30.80	-	-
	Total Rainfall Duration (minutes)	94.00	-	-
	Maximum Intensity (mm)	60.00	-	-
February	Mean Daily Total Rainfall (mm/day)	2.50	2.64	5.6
	Maximum Daily Total Rainfall (mm/day)	17.20	24.96	45.1
	Total Rainfall (mm)	72.60	76.54	5.4
	Total Rainfall Duration (minutes)	193.00	730.00	278.2
	Maximum Intensity (mm)	144.00	141.56	-1.7
March	Mean Daily Total Rainfall (mm/day)	3.19	3.12	-2.2
	Maximum Daily Total Rainfall (mm/day)	54.20	53.62	-1.1
	Total Rainfall (mm)	98.80	96.62	-2.2
	Total Rainfall Duration (minutes)	95.00	226.00	137.9
	Maximum Intensity (mm)	180.00	172.25	-4.3
April	Mean Daily Total Rainfall (mm/day)	1.27	1.63	28.3
	Maximum Daily Total Rainfall (mm/day)	24.40	18.80	-23.0
	Total Rainfall (mm)	38.00	48.93	28.8
	Total Rainfall Duration (minutes)	62.00	304.00	390.3
	Maximum Intensity (mm)	156.00	159.09	2.0
May	Mean Daily Total Rainfall (mm/day)	5.94	4.24	-28.6
	Maximum Daily Total Rainfall (mm/day)	35.80	33.95	-5.2
	Total Rainfall (mm)	184.20	131.29	-28.7
	Total Rainfall Duration (minutes)	549.00	1663.00	202.9
	Maximum Intensity (mm)	120.00	117.68	-1.9
June	Mean Daily Total Rainfall (mm/day)	2.29	2.09	-8.7
	Maximum Daily Total Rainfall (mm/day)	45.40	41.42	-8.8
	Total Rainfall (mm)	68.80	62.57	-9.1
	Total Rainfall Duration (minutes)	211.00	970.00	359.7
	Maximum Intensity (mm)	108.00	106.85	-1.1
July	Mean Daily Total Rainfall (mm/day)	6.55	5.20	-20.6
	Maximum Daily Total Rainfall (mm/day)	73.80	48.63	-34.1
	Total Rainfall (mm)	203.00	161.30	-20.5
	Total Rainfall Duration (minutes)	418.00	1285.00	207.4
	Maximum Intensity (mm)	180.00	163.62	-9.1
Overall	Mean Daily Total Rainfall (mm/day)	3.25	3.15	3.08
	Maximum Daily Total Rainfall (mm/day)	73.80	53.62	27.3
	Total Rainfall (mm)	696.20	577.25	17.09
	Total Rainfall Duration (minutes)	1622.00	5178.00	-219.2
	Maximum Intensity (mm)	180.00	172.30	-4.3

Table 4.7. Basic statistics for Station Subang.

Month	Rainfall Parameters	TBRG	Thies	Difference (%)
January	Mean Daily Total Rainfall (mm/day)	7.79	-	-
	Maximum Daily Total Rainfall (mm/day)	49.80	-	-
	Total Rainfall (mm)	241.40	-	-
	Total Rainfall Duration (minutes)	591.00	-	-
	Maximum Intensity (mm)	120.00	-	-
February	Mean Daily Total Rainfall (mm/day)	2.45	3.13	27.8
	Maximum Daily Total Rainfall (mm/day)	19.20	24.55	27.9
	Total Rainfall (mm)	71.00	90.85	28.0
	Total Rainfall Duration (minutes)	194.00	590.00	204.1
	Maximum Intensity (mm)	72.00	148.52	106.3
March	Mean Daily Total Rainfall (mm/day)	4.59	7.49	63.2
	Maximum Daily Total Rainfall (mm/day)	31.40	64.66	105.9
	Total Rainfall (mm)	142.40	232.19	63.1
	Total Rainfall Duration (minutes)	296.00	785.00	165.2
	Maximum Intensity (mm)	120.00	260.38	117.0
April	Mean Daily Total Rainfall (mm/day)	8.19	13.57	65.7
	Maximum Daily Total Rainfall (mm/day)	102.00	92.03	-9.8
	Total Rainfall (mm)	245.60	407.03	65.7
	Total Rainfall Duration (minutes)	396.00	1178.00	197.5
	Maximum Intensity (mm)	204.00	356.05	74.5
May	Mean Daily Total Rainfall (mm/day)	11.90	18.72	57.3
	Maximum Daily Total Rainfall (mm/day)	64.80	135.39	108.9
	Total Rainfall (mm)	368.80	580.31	57.4
	Total Rainfall Duration (minutes)	842.00	2506.00	197.6
	Maximum Intensity (mm)	192.00	483.05	151.6
June	Mean Daily Total Rainfall (mm/day)	6.11	9.24	51.2
	Maximum Daily Total Rainfall (mm/day)	65.20	85.66	31.4
	Total Rainfall (mm)	183.40	277.34	51.2
	Total Rainfall Duration (minutes)	433.00	1396.00	222.4
	Maximum Intensity (mm)	120.00	228.51	90.4
July	Mean Daily Total Rainfall (mm/day)	7.49	12.20	62.9
	Maximum Daily Total Rainfall (mm/day)	63.40	105.94	67.1
	Total Rainfall (mm)	232.20	378.24	62.9
	Total Rainfall Duration (minutes)	528.00	1718.00	225.4
	Maximum Intensity (mm)	216.00	484.96	124.5
Overall	Mean Daily Total Rainfall (mm/day)	6.93	10.72	54.69
	Maximum Daily Total Rainfall (mm/day)	102.00	135.39	32.7
	Total Rainfall (mm)	1484.8	1965.96	-32.4
	Total Rainfall Duration (minutes)	3280.00	8173.00	-149.2
	Maximum Intensity (mm)	216.0	484.96	124.5

The time series of daily total rainfall amount, daily total rainfall duration, daily maximum rainfall intensity and percentages of differences for each sensors with respect to reference tipping bucket rain gauge for Melaka station are shown in Figure 4.4 - 4.6. The daily rainfall amount observed by Thies were obviously higher than those measured by tipping bucket especially during the wetter month and heavy rain events (Figure 4.4(a)). Some of these are doubled of the rainfall amount measurement by tipping bucket. OTT and VXT capture the day-to-day evolution of rainfall amount reasonably well. However, there is a spike found occurred in OTT measurement on the last week of June. There is a tendency that the differences of rainfall amount found increase with the increase of rainfall amount measured by tipping bucket.

Both the daily total rainfall duration and daily maximum rainfall intensity were showing the same trend as the day-to-day evolution of rainfall amount. Differences are larger during the wetter months such as May and June for all sensors. VXT shows the least deviation from tipping bucket in total rainfall duration and maximum rainfall intensity among the three sensors. VXT is the only sensor recorded lower rainfall duration with respect to tipping bucket at Melaka station (Figure 4.5(d)), as compared with OTT and Thies. The rainfall duration recorded by both OTT and Thies are closer to each other in the rainfall events. For the daily maximum rainfall intensity, OTT and VXT show a better agreement to those recorded by tipping bucket (Figure 4.6(c) and 4.6(d)). However, there is a spike found in the beginning of the measurement period in the daily total rainfall duration measured by OTT (Figure 4.5(a)) and daily maximum rainfall intensity observed by Thies (Figure 4.6(a)). Overall, there is a tendency where the differences in these three parameters increase towards the end of the measurement campaign in Melaka station.

Figure 4.7 – 4.9 displayed the time series of daily total rainfall amount, daily total rainfall duration, daily maximum rainfall intensity and percentages of differences for Thies with respect to reference tipping bucket rain gauge for Mersing station. Thies was able to capture the daily evolution of rainfall in Mersing with some degrees of deviation from the tipping bucket measurement. Rainfall measurement made by Thies in January, part of February and June was not shown in those figures due the high percentage of missing data in a day.

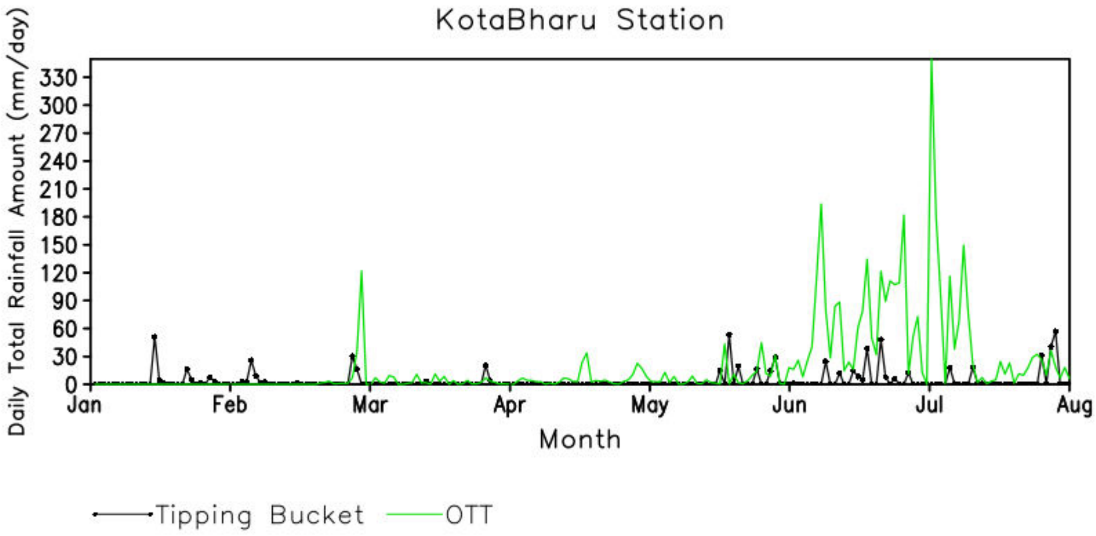
The daily rainfall amount observed by Thies in Mersing station showed a similar trend to comparison of daily total rainfall amount between Thies and tipping bucket at Melaka station.

Higher daily total rainfall amount, daily total rainfall duration and maximum rainfall intensity were observed by Thies than those recorded tipping bucket during the wetter month and heavy rain events (Figure 4.7(a), 4.8(a) and 4.9 (a)). Some of these are more than double of the rainfall measurement by tipping bucket events (Figure 4.7(b), 4.8(b) and 4.9 (b)). A tendency similar the measurement made by Thies sensor in Melaka station was found in Mersing, where the differences of rainfall amount and duration increase with the increase of rainfall amount and duration measured by tipping bucket. Both the daily total rainfall duration (Figure 4.8(a)) and daily maximum rainfall intensity (Figure 4.9(a)) were showing the same trend as the day-to-day evolution of rainfall amount.

Figure 4.10 – 4.12 depict the time series of daily total rainfall amount, daily total rainfall duration, daily maximum rainfall intensity and percentages of differences for OTT with respect to reference tipping bucket rain gauge for Sitiawan station. Part of rainfall measurement made by OTT in January were not plotted in those figures due the high percentage of missing data in a day. OTT was able to capture the day to day evolution of rainfall amount in with smaller deviation from the tipping bucket measurement (Figure 4.10). It was found that OTT was measuring a lower daily rainfall amount with respect to those measured by tipping bucket in some of heavy rainfall events at Sitiawan (Figure 4.11). Daily maximum rainfall intensity observed by OTT were close to those derived from tipping bucket (Figure 4.12). The maximum rainfall intensity measured by OTT sensor was generally lower than those measured by tipping bucket.

The time series of daily total rainfall amount, daily total rainfall duration, daily maximum rainfall intensity and percentages of differences for Thies with respect to reference tipping bucket rain gauge for last station, Subang station were shown in Figure 4.13 – 4.15. Part of rainfall measurement made by Thies in January were not plotted in those figures due the high percentage of missing values in a day. From Figure 4.13, Thies was able to capture the day to day evolution of rainfall amount similar to tipping bucket measurement. However, the differences are relatively large especially during heavy rainfall events with respect to tipping bucket measurement (Figure 4.13(b)). Similar to rainfall amount, the daily total rainfall duration and maximum rainfall intensity of Thies were always higher than those from tipping bucket (Figure 4.14 and 4.15). Thies measured lower maximum rainfall intensity in some of the lighter rainfall events (Figure 4.15(a)).

(a)



(b)

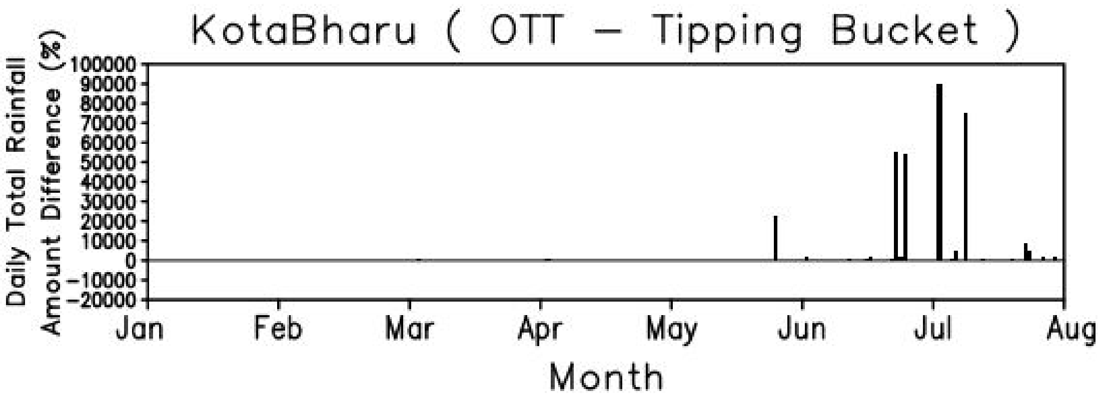


Figure 4.1. Time series of (a) daily total rainfall amount (mm/day) and (b) its differences with respect to reference tipping bucket rain gauge for Kota Bahru Station.

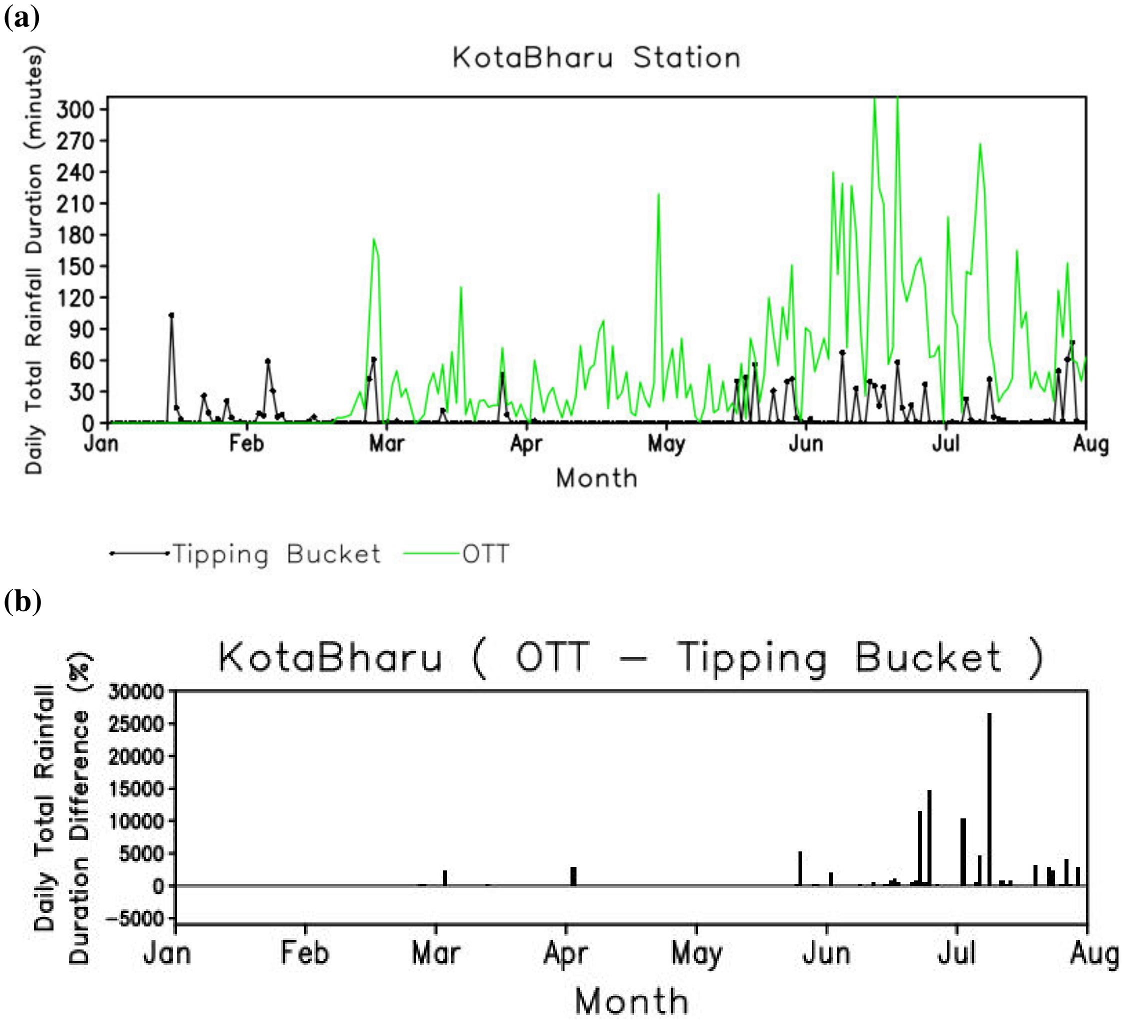
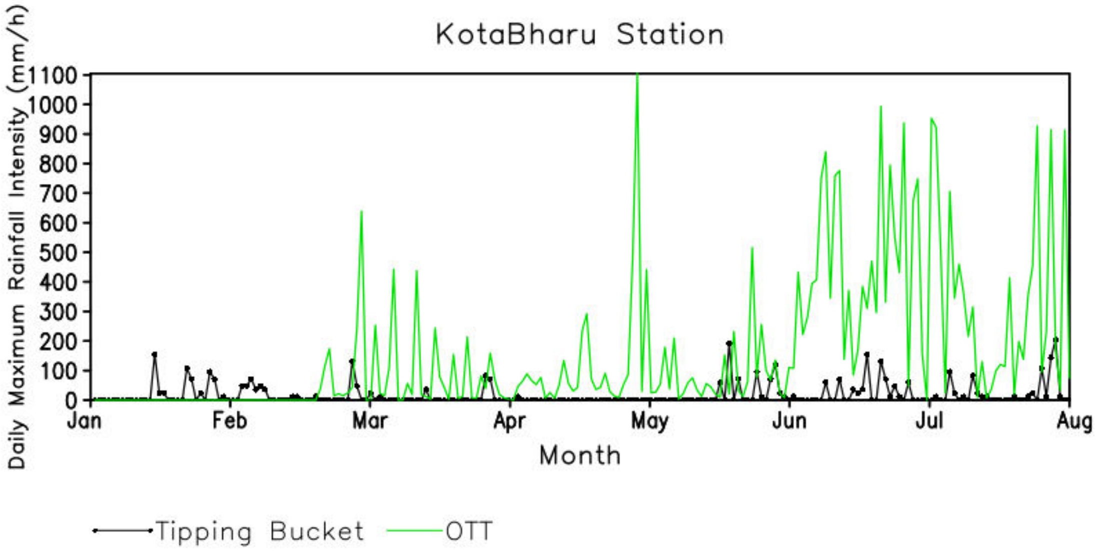


Figure 4.2. Time series of (a) daily total rainfall duration (minutes) and (b) its differences with respect to reference tipping bucket rain gauge for Kota Bahru Station.

(a)



(b)

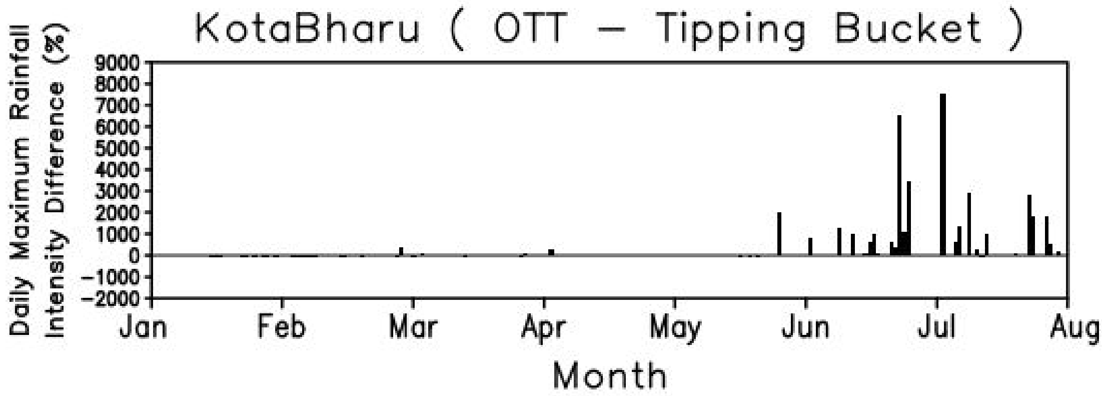


Figure 4.3. Time series of (a) daily maximum rainfall intensity (mm/h) and (b) its differences with respect to reference tipping bucket rain gauge for Kota Bahru Station.

(a)

(b)

(c)

(d)

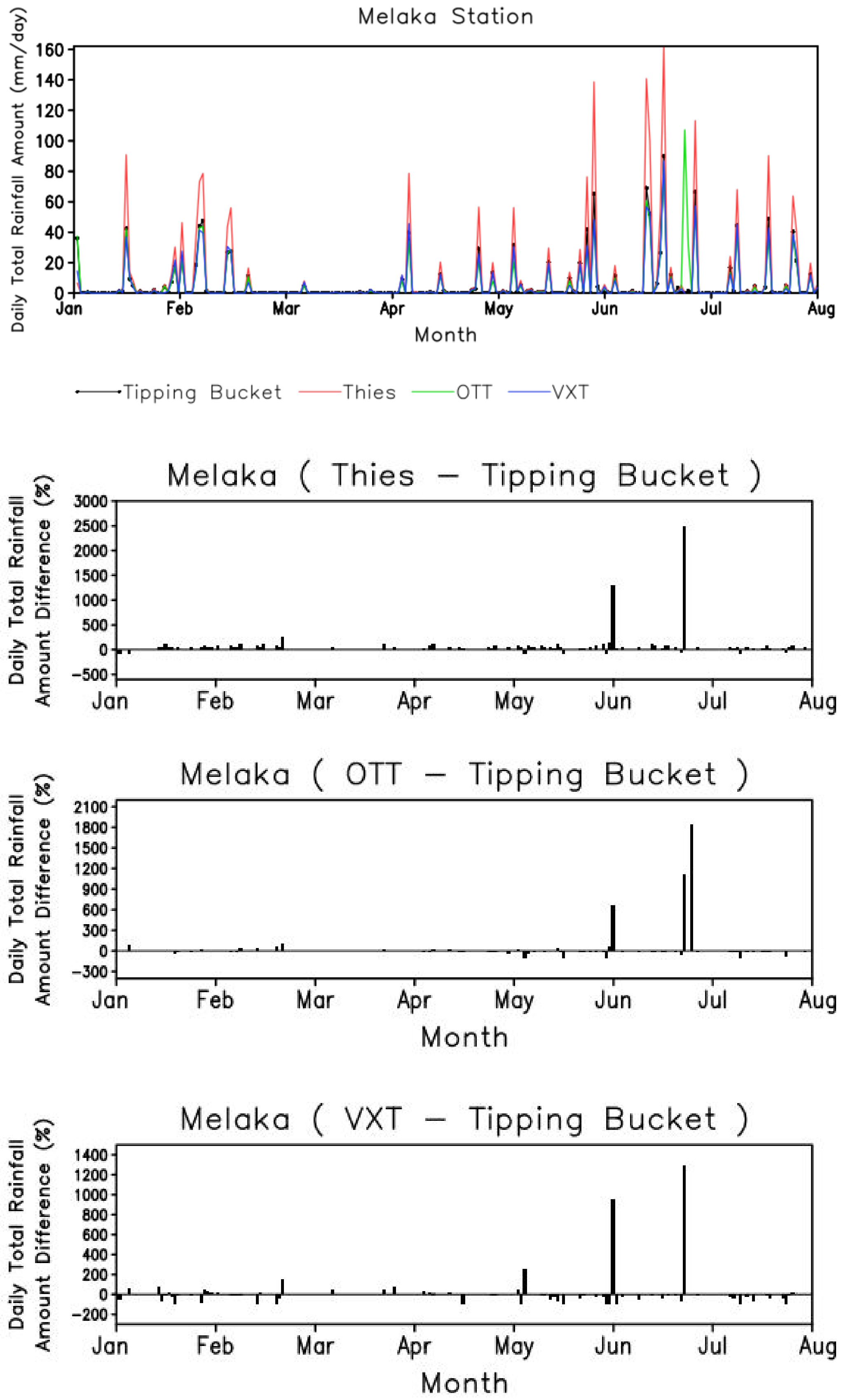
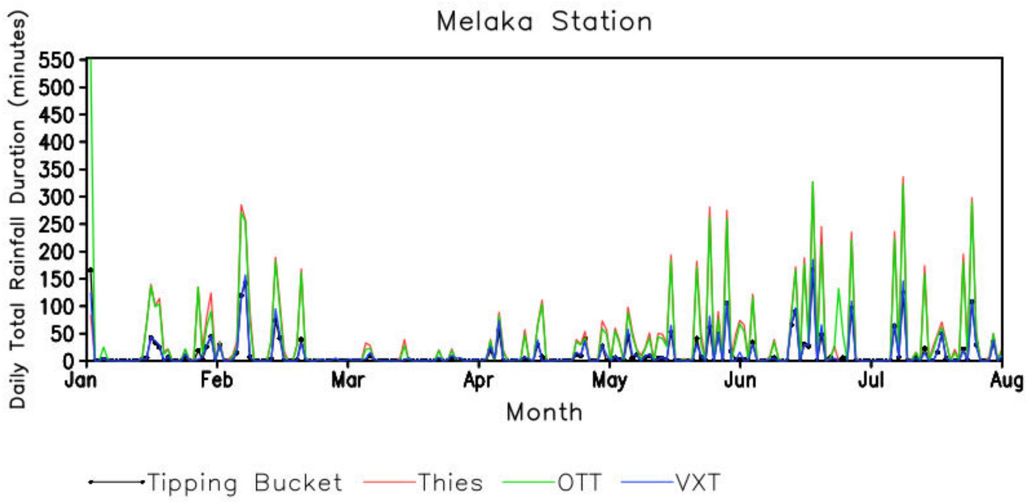
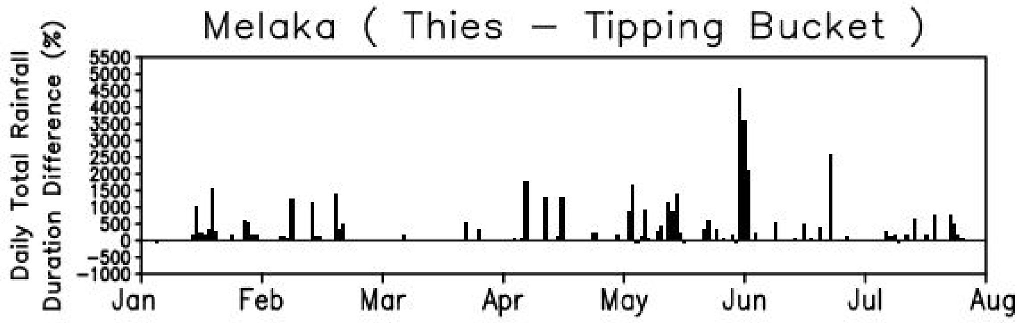


Figure 4.4. Time series of (a) daily total rainfall amount (mm/day) and (b-d) its differences for each sensor with respect to reference tipping bucket rain gauge for Melaka Station.

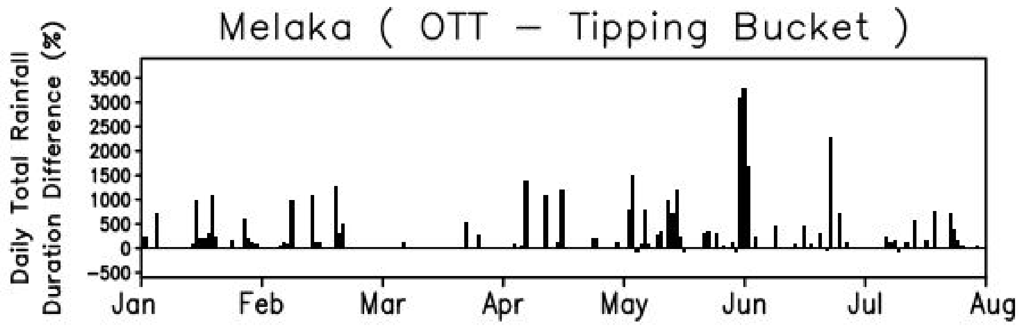
(a)



(b)



(c)



(d)

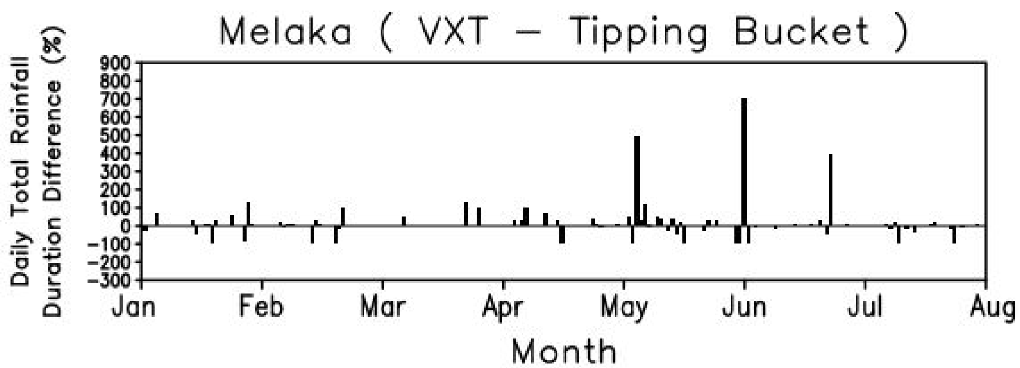


Figure 4.5. Time series of (a) daily total rainfall duration (minutes) and (b-d) its differences for each sensor with respect to reference tipping bucket rain gauge for Melaka Station.

(a) (b) (c) (d)

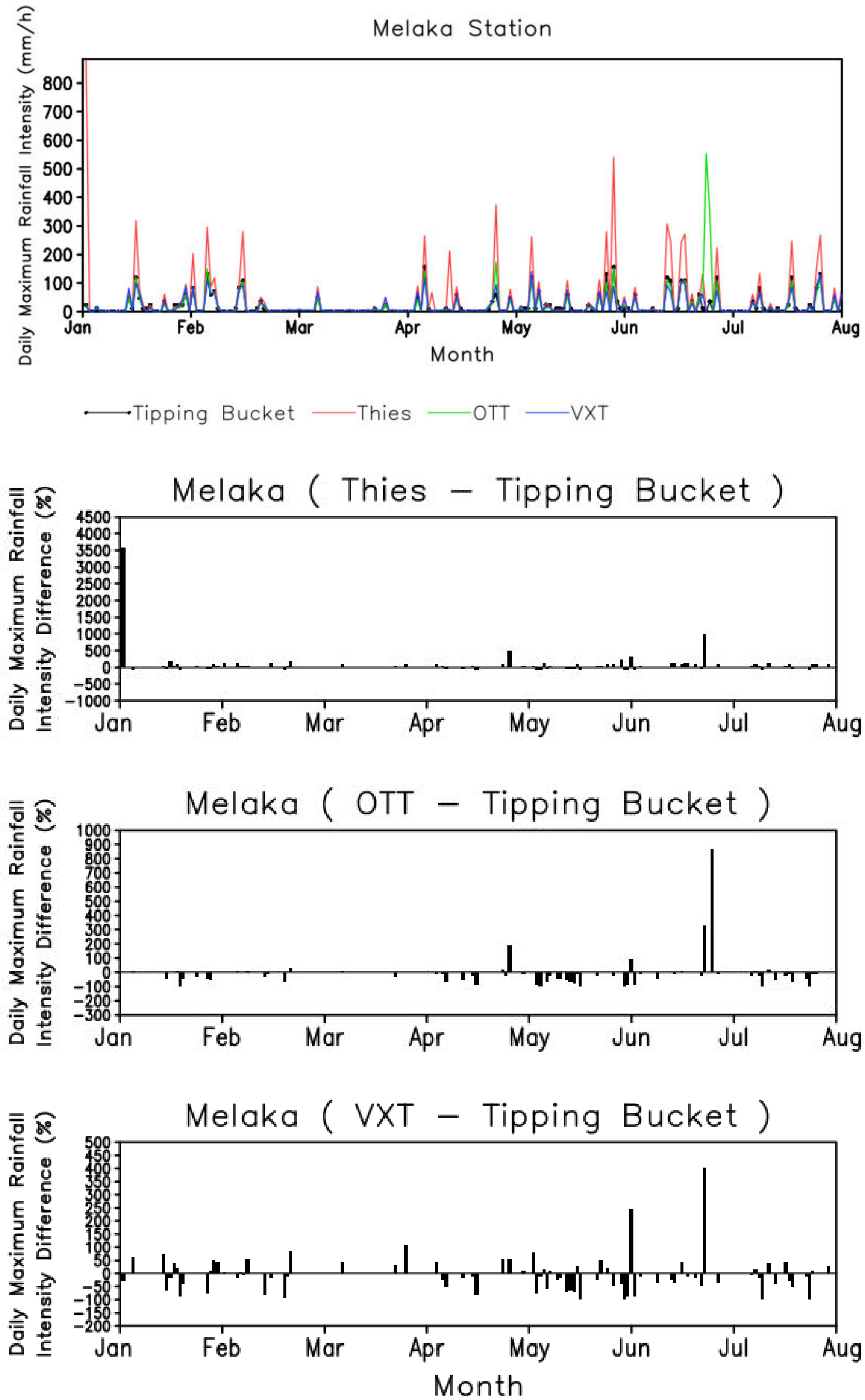
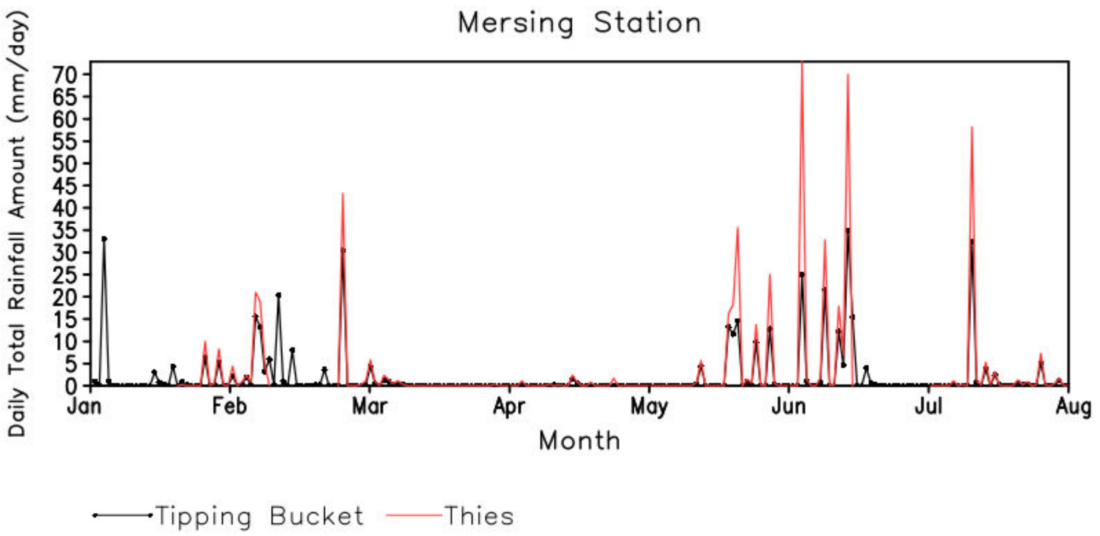


Figure 4.6. Time series of (a) daily maximum rainfall intensity (mm/h) and (b-d) its differences for each sensors with respect to reference tipping bucket rain gauge for Melaka Station.

(a)



(b)

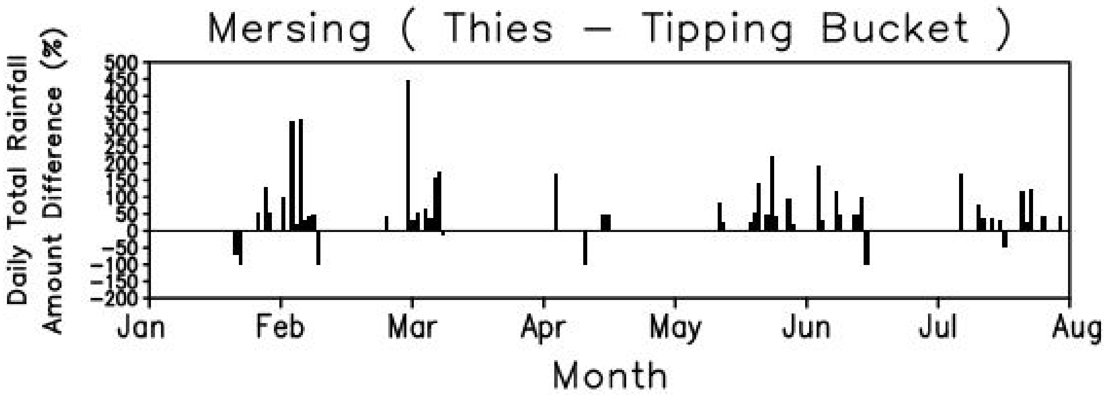
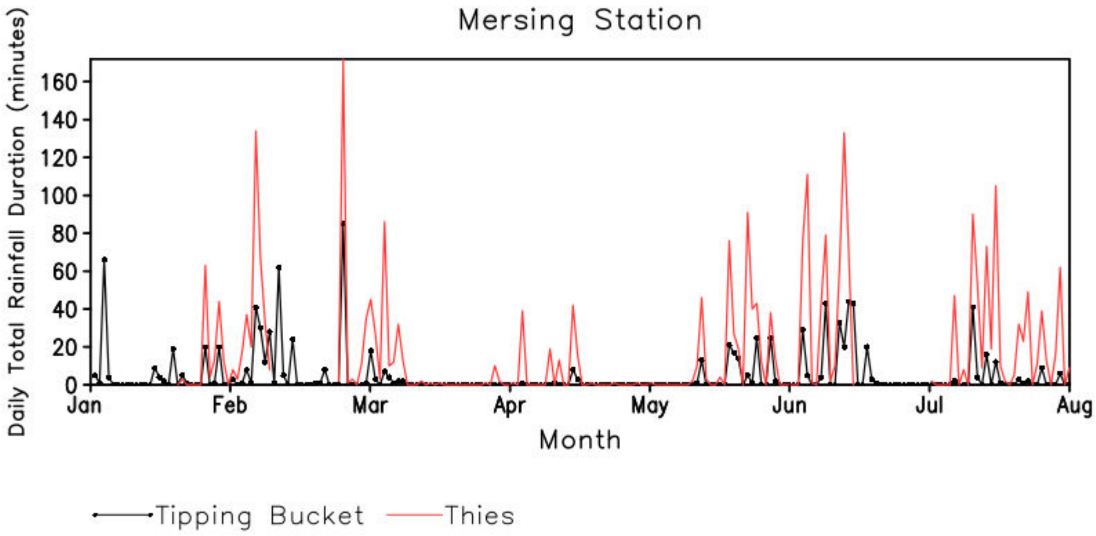


Figure 4.7. Time series of (a) daily total rainfall amount (mm/day) and (b) its differences for each sensor with respect to reference tipping bucket rain gauge for Mersing Station.

(a)



(b)

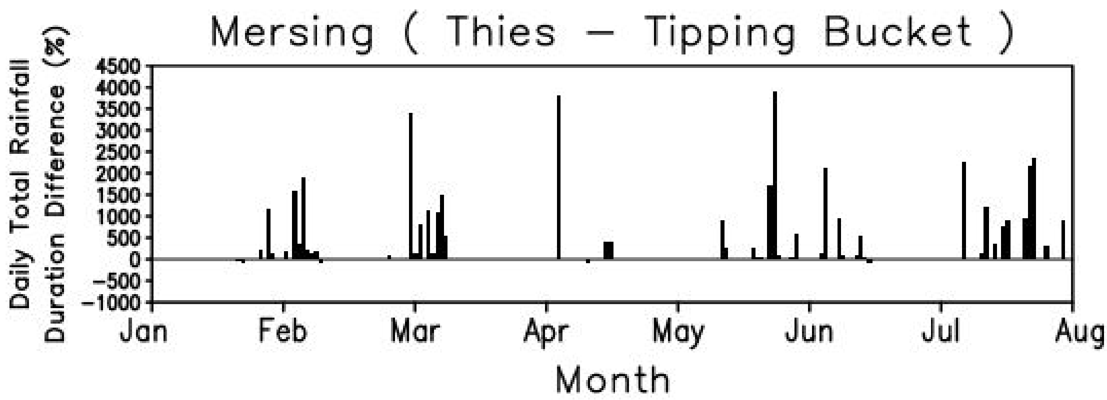
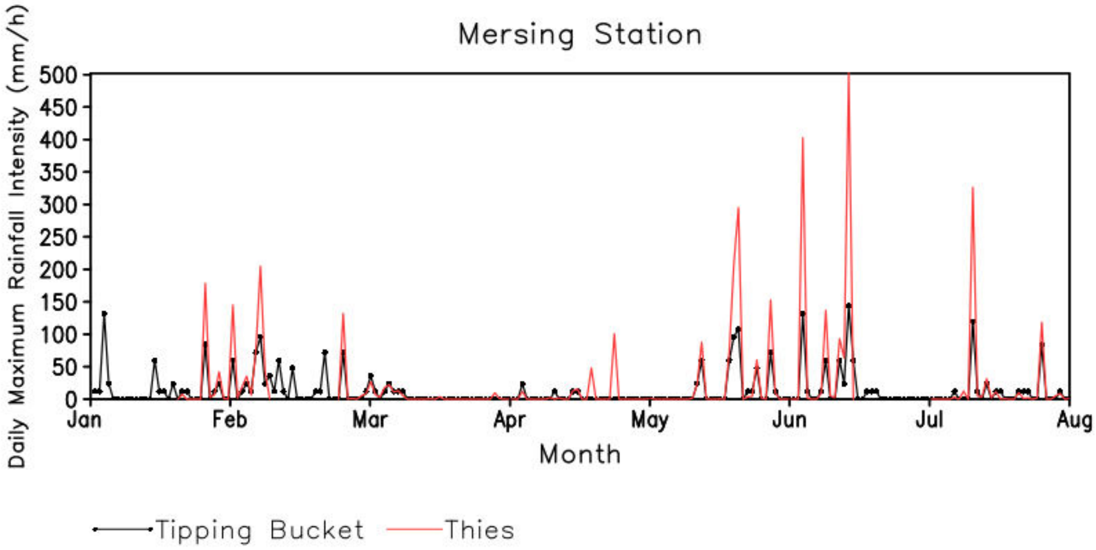


Figure 4.8. Time series of (a) daily total rainfall duration (minutes) and (b) its differences for each sensor with respect to reference tipping bucket rain gauge for Mersing Station.

(a)



(b)

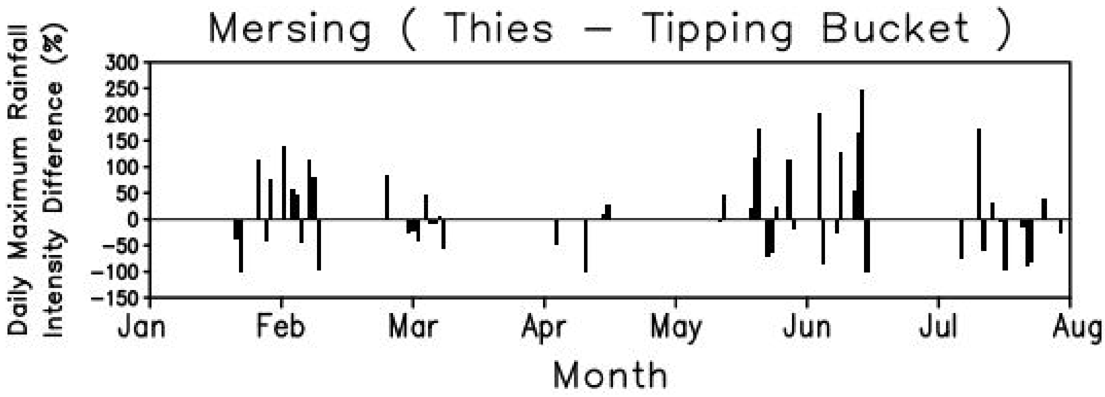


Figure 4.9. Time series of (a) daily maximum rainfall intensity (mm/h) and (b) its differences for each sensors with respect to reference tipping bucket rain gauge for Mersing Station.

(a)

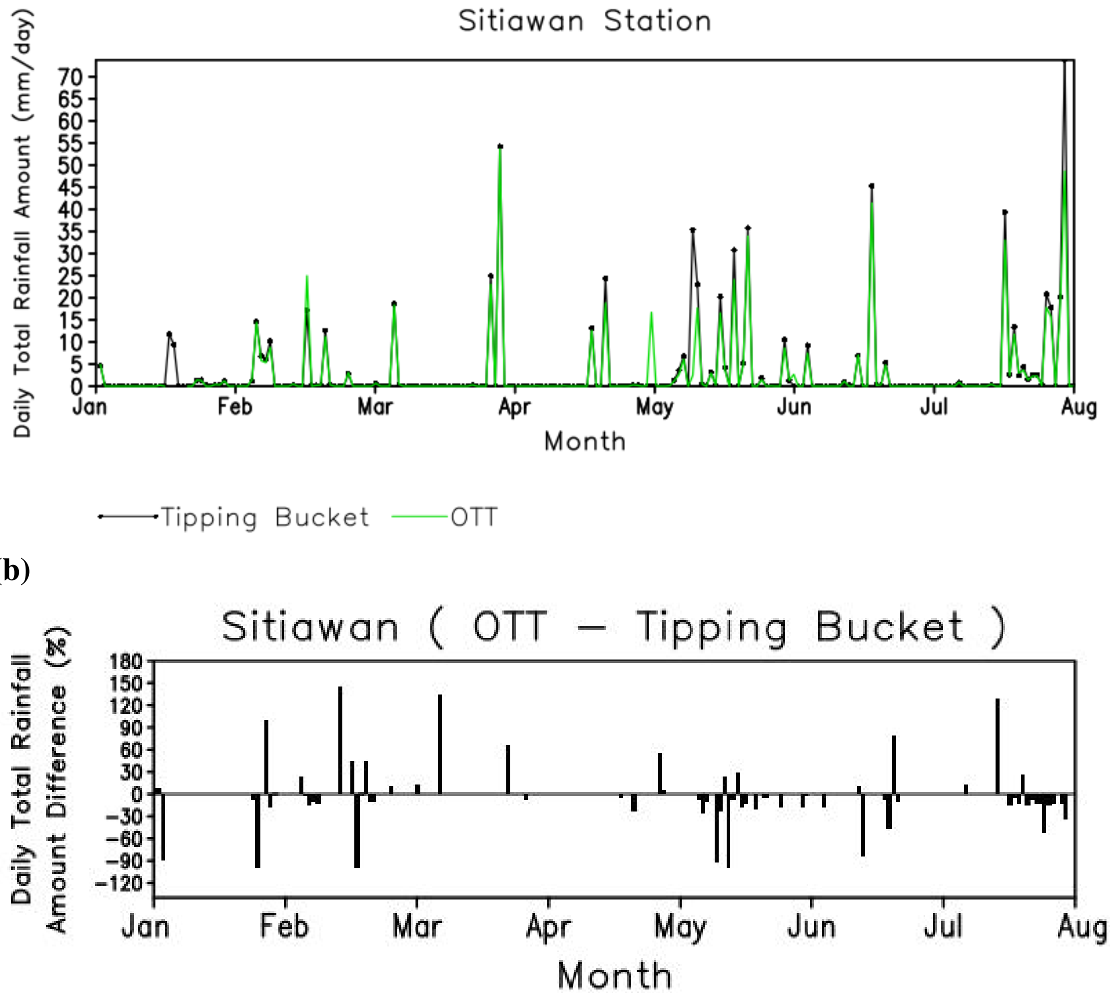
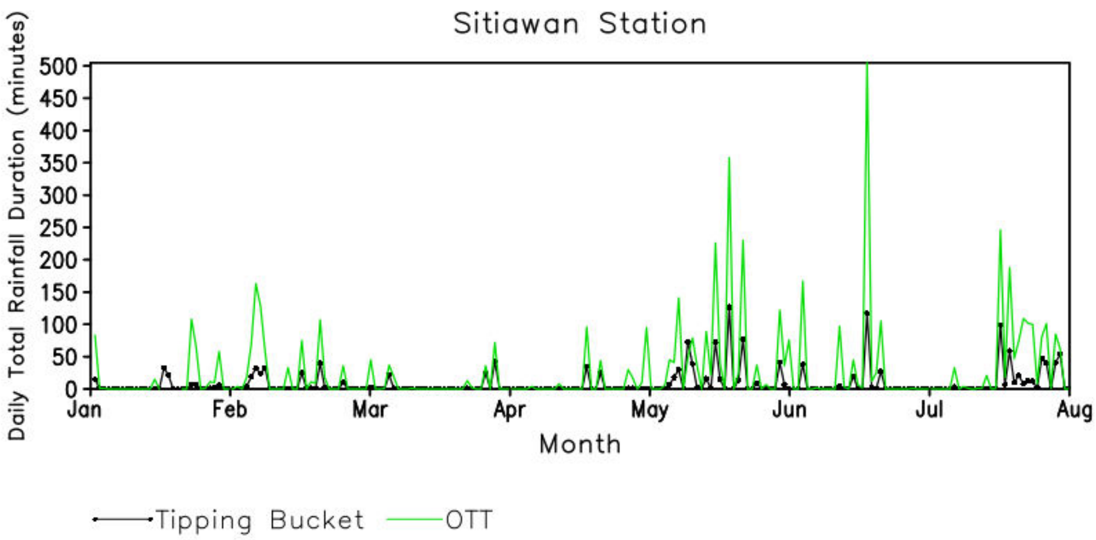


Figure 4.10. Time series of (a) daily total rainfall amount (mm/day) and (b) its differences for each sensor with respect to reference tipping bucket rain gauge for Sitiawan Station.

(a)



(b)

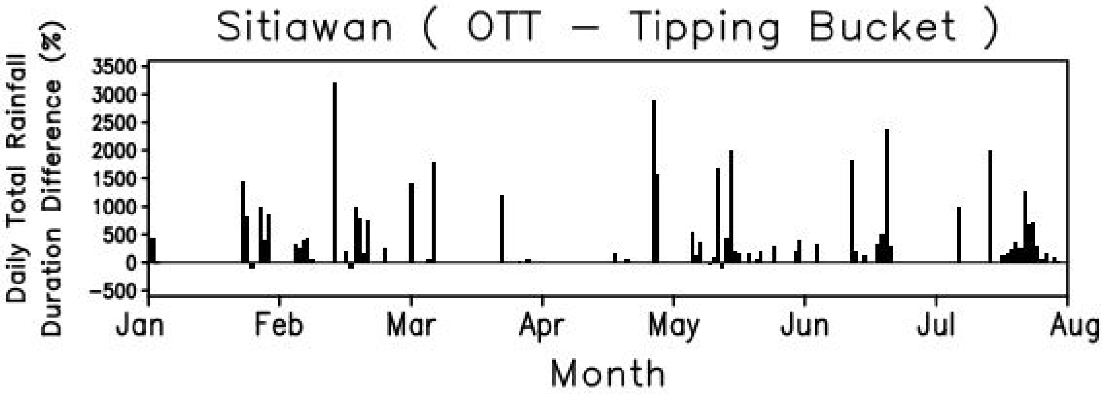
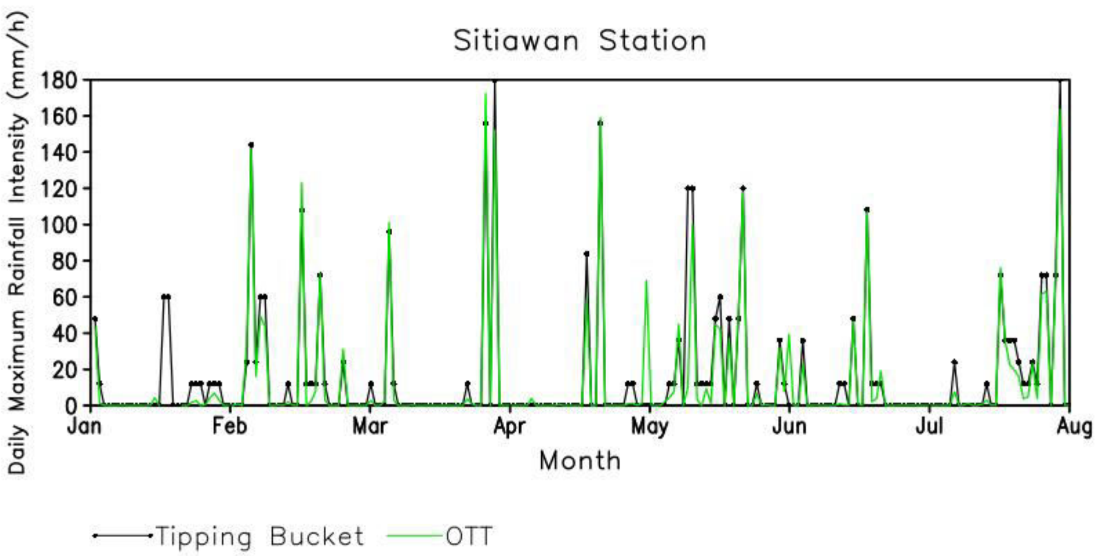


Figure 4.11. Time series of (a) daily total rainfall duration (minutes) and (b) its differences for each sensor with respect to reference tipping bucket rain gauge for Sitiawan Station.

(a)



(b)

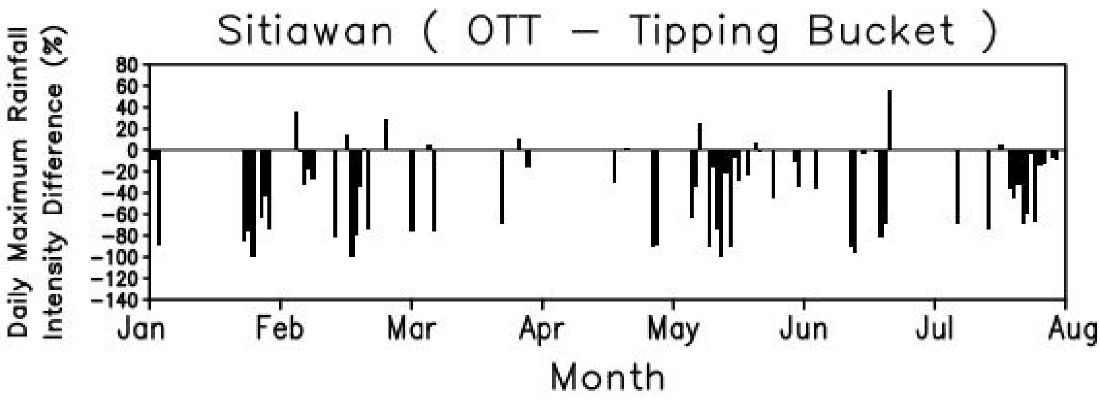


Figure 4.12. Time series of (a) daily maximum rainfall intensity (mm/h) and (b) its differences for each sensors with respect to reference tipping bucket rain gauge for Sitiawan Station.

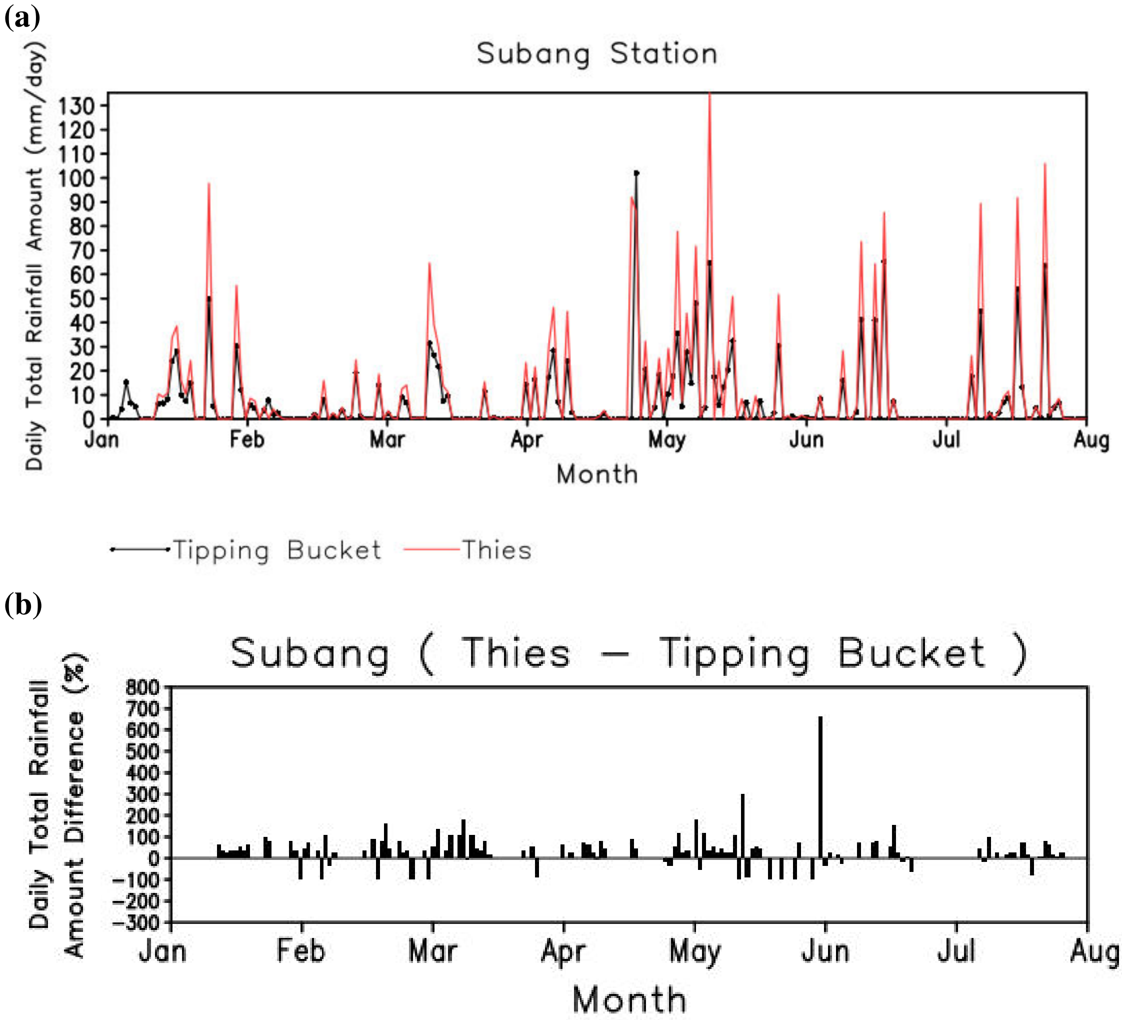
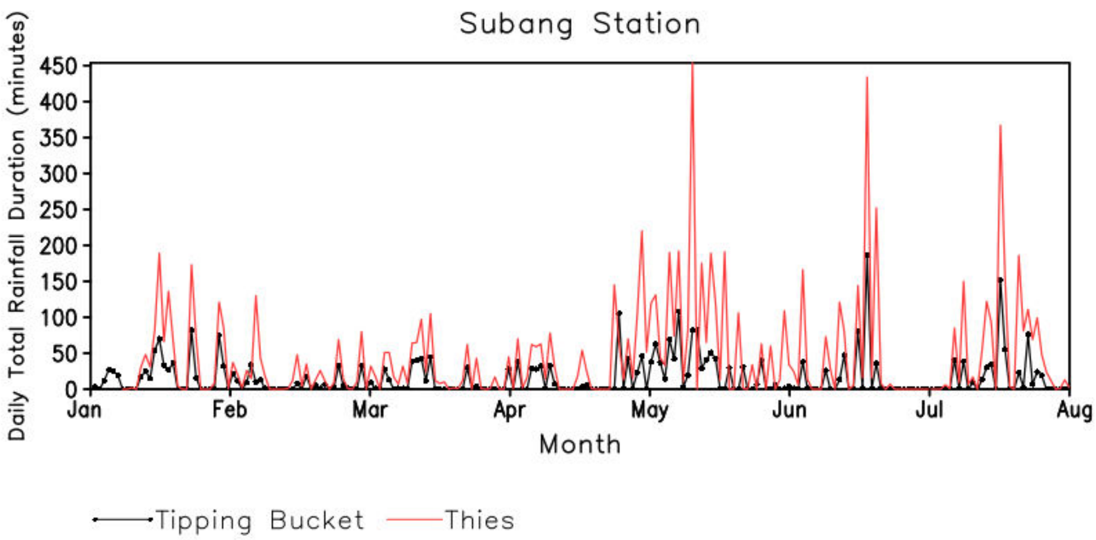


Figure 4.13. Time series of (a) daily total rainfall amount (mm/day) and (b) its differences for each sensor with respect to reference tipping bucket rain gauge for Subang Station.

(a)



(b)

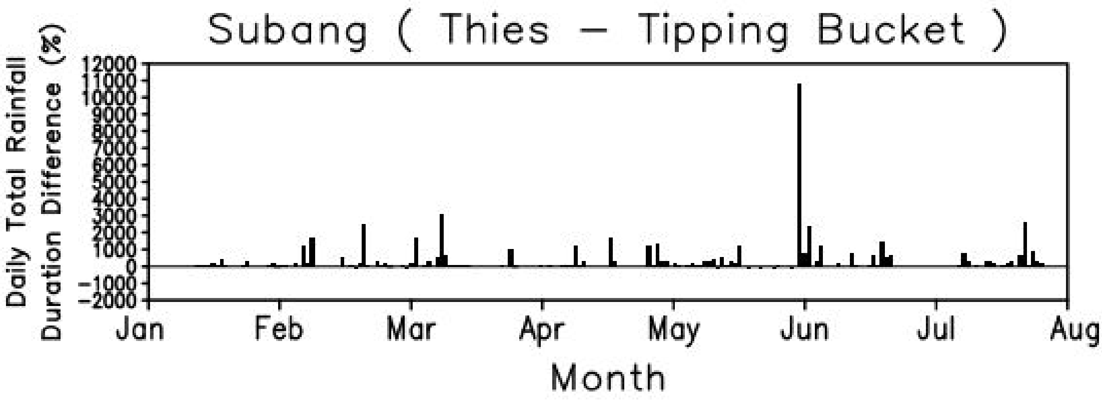
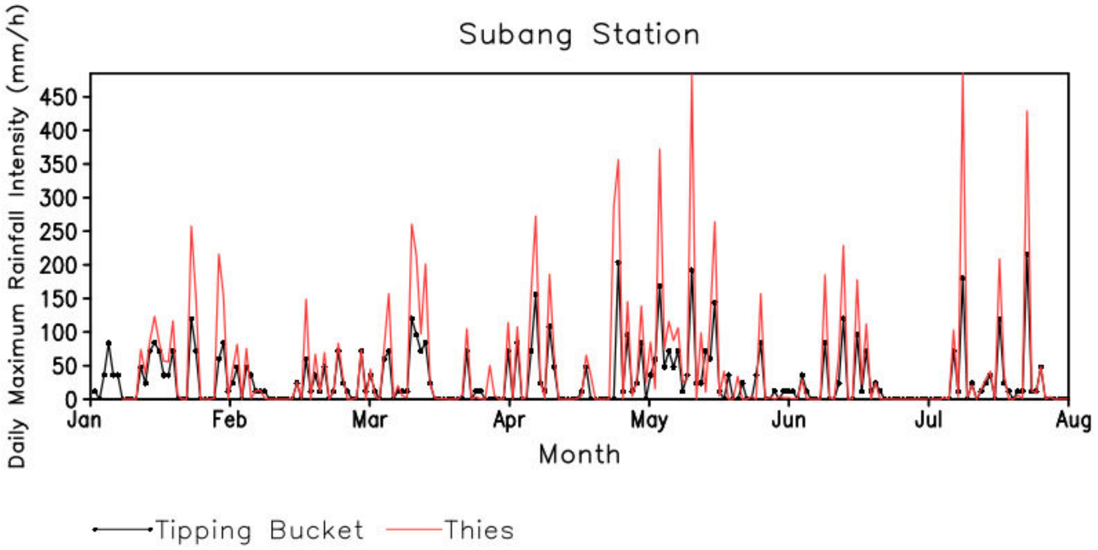


Figure 4.14. Time series of (a) daily total rainfall duration (minutes) and (b) its differences for each sensor with respect to reference tipping bucket rain gauge for Subang Station.

(a)



(b)

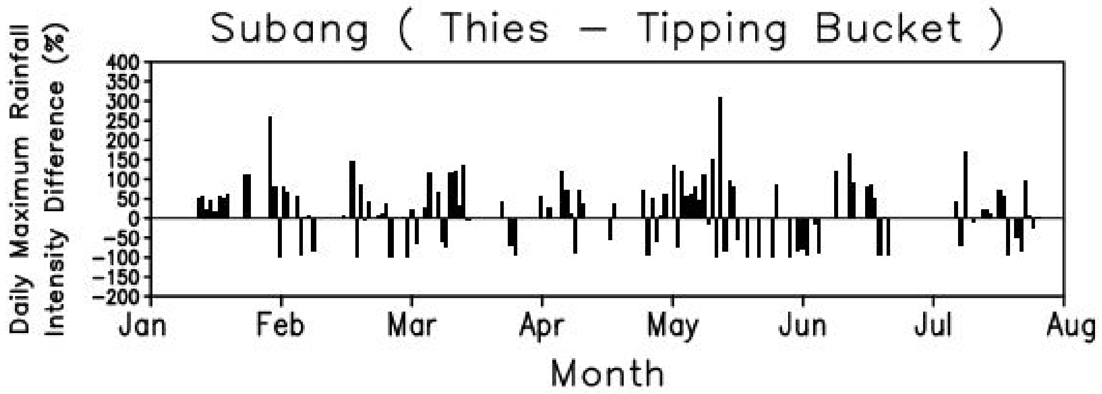


Figure 4.15. Time series of daily maximum rainfall intensity (mm/h) and its differences for each sensors with respect to reference tipping bucket rain gauge for Kota Bahru Station.

From the time series of daily rainfall, we could hardly see the specific performance of each instrument. In order to assess the specific performance of each instrument, further comparison analysis have been done to OTT, Thies and VXT to discuss the details of rainfall observed by each instrument. The tipping bucket rain gauge can recorded the rainfall amount precisely, therefore it is taken as a reference in all of the comparison. The correlation coefficient and student-t test was conducted to test on the agreement of the rainfall measurement made by individual instrument with that of tipping bucket.

Figure 4.16-4.18 depict the comparison of rainfall amount, duration and rainfall intensity observed by individual instrument against the reference tipping bucket rain gauge for the different period of measurement campaign (January to July) at Melaka.

The rainfall amount from Thies has the largest scatter as compared to other instruments (Figure 4.16 (a). Most of the data recorded were fall above the 1:1 line, which indicate that Thies recorded higher rainfall amount with respect to Thies for Melaka for all period, including Northeast monsoon, inter-monsoon and Southwest monsoon. OTT, Thies and VXT measured the evolution of minute-by-minute rainfall amount reasonably well with the correlation range between 0.47 – 0.61. Those instruments show a better agreement in the minute-by-minute evolution rainfall amount during the Northeast monsoon period (Figure 4.16(d), 4.17(d) and 4.18(d)), where all the instrument were highly correlated with the reference tipping bucket. Lower correlation found in the rainfall amount for all instruments during the wetter months such as those occurred in Southwest Monsoon in Melaka. Large differences in rainfall amount between OTT and tipping bucket was found occurred during the wetter month in Southwest Monsoon (Figure 4.17(j)). Rainfall intensity shared a similar features observed in rainfall amount comparison between instruments and reference, such as better agreement between all instrument measurement with respect to reference during Northeast Monsoon (Figure 4.16(f), 4.17(f) and 4.18(f)), and most of the rainfall intensity recorded were higher that reference measurement.

Rainfall duration recorded by Thies and OTT was generally much higher than reference tipping bucket record especially during the wetter month such as Northeast Monsoon (Figure 4.16 (e), 4.17(e)) and Southwest Monsoon (Figure 4.16 (k) and 4.17(k)). The differences may due to the lower resolution of tipping bucket. The evolution of minute-by-minute rainfall duration were well captured by all the instruments with all the correlations more than 0.7 for all measurement period. The correlation of rainfall duration recorded by VXT was extraordinary high with all the R value were higher than 0.94 with overall R=0.95 (middle column of Figure 4.18).

For Mersing station, the comparison of rainfall amount, duration and rainfall intensity observed by Thies against the reference tipping bucket rain gauge for the different period of measurement campaign (January to July) are shown in Figure 4.19. Similar to the comparison of rainfall measurement recorded by Thies at Melaka station, most of the rainfall amount, intensity and duration were fall well above the 1:1 line, which indicates rainfall amount, intensity and duration made by Thies are higher than those recorded by tipping bucket. It is interesting to find that Thies measured the rainfall in Mersing well during Southwest Monsoon with R=0.9 for both rainfall amount and intensity (Figure 4.19 (j) and (l)). During inter-monsoonal period, where rainfall recorded are significantly low, Thies recorded more rainfall occurrence where the rainfall amount less than 0.2 mm/min and less occurrence for rainfall amount ≥ 0.2mm/min (Figure 4.19(d)). Higher duration are observed by Thies during this period (Figure 4.19(h)).

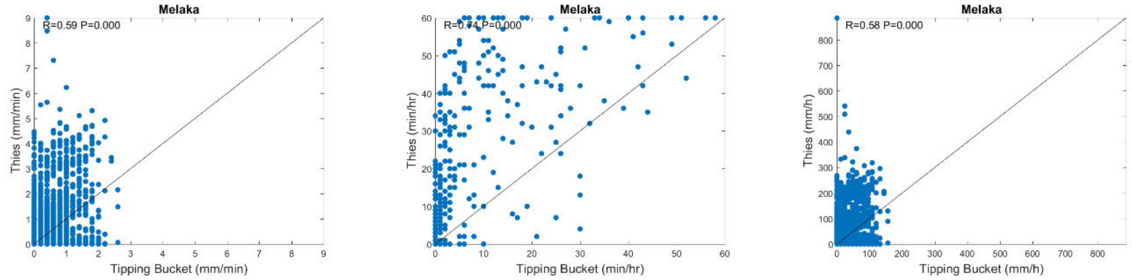
Another comparison of rainfall amount, duration and rainfall intensity observed by Thies against the reference tipping bucket rain gauge for the different period of measurement campaign (January to July) at Subang station are shown in Figure 4.20. Once again, similar to the comparison of rainfall measurement recorded by Thies at Melaka and Mersing station, most of the rainfall amount, intensity and duration were fall well above the 1:1 line, which indicates rainfall amount, intensity and duration made by Thies are higher than those recorded by tipping bucket. However, the correlation of rainfall measurement between Thies and reference tipping bucket at this station are relatively low, as compared to Thies measurement made at other stations. The overall correlation for rainfall amount and intensity were 0.34 and 0.4 for rainfall duration. Thies was unable to capture the rainfall characteristics at Subang station especially during drier month, the inter-monsoonal period (third row of Figure 4.20).

Lastly, the comparison of rainfall amount, duration and rainfall intensity observed by OTT against the reference tipping bucket rain gauge for the different period of measurement campaign (January to July) at Sitiawan station are shown in Figure 4.21. OTT measured rainfall amount, duration and intensity relatively well with respect to reference tipping bucket. The evolution of minute-by-minute rainfall amount, duration and intensity were well captured by OTT with all the correlations more than 0.7 for all measurement period. The correlation of rainfall amount and intensity recorded by OTT are extraordinary high with all the R were higher than 0.92 with overall R=0.93 (left column of Figure 4.21). No large differences were found during heavy rainfall events such as those observed in Melaka station.

Rainfall Amount (mm/min) | **Rainfall Duration (min/hr)** | **Rainfall Intensity**

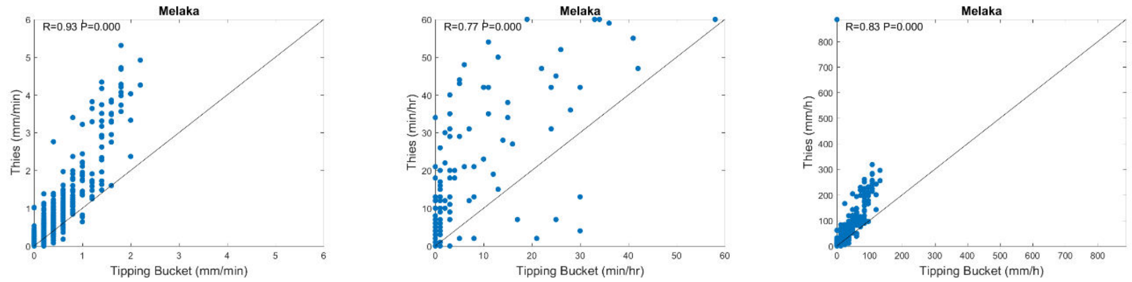
Full record

(a) (b) (c)



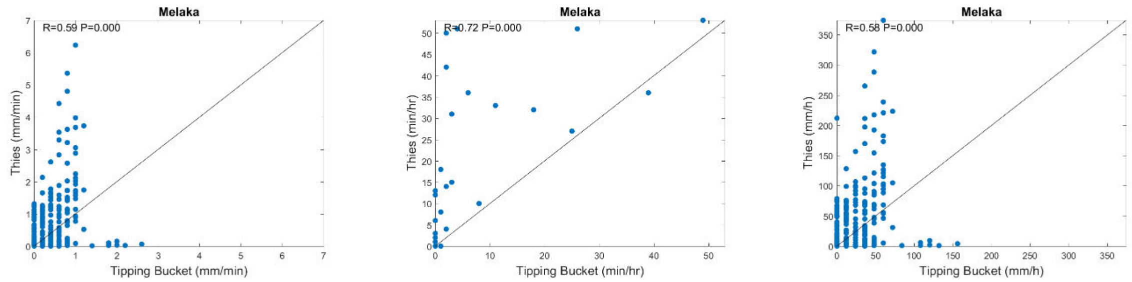
Northeast Monsoon

(d) (e) (f)



Inter-monsoonal period

(g) (h) (i)



Southwest Monsoon

(j) (k) (l)

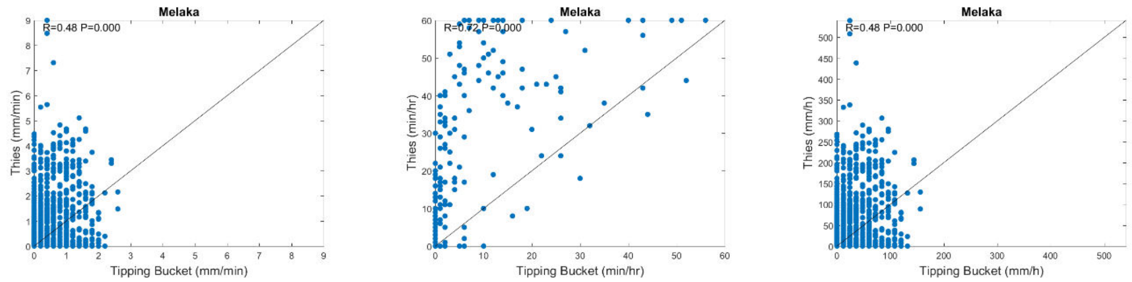
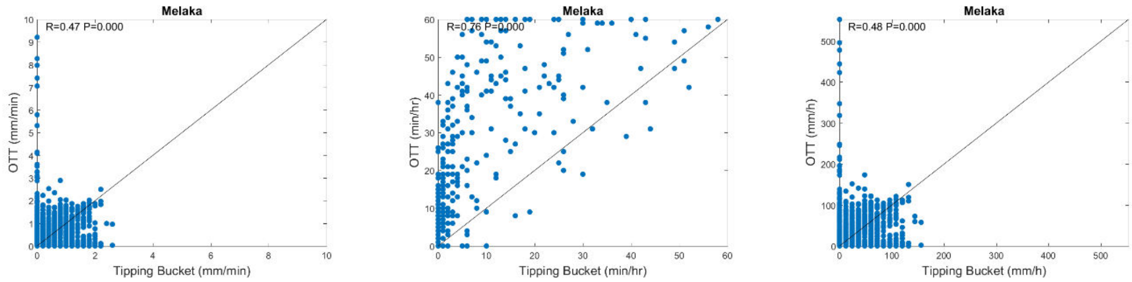


Figure 4.16. Comparison of rainfall amount, duration and rainfall intensity from Thies against reference tipping bucket for different measurement periods at Melaka station. The correlation, R and p-values are shown at the upper left corner.

Rainfall Amount (mm/min) | **Rainfall Duration (min/hr)** | **Rainfall Intensity**

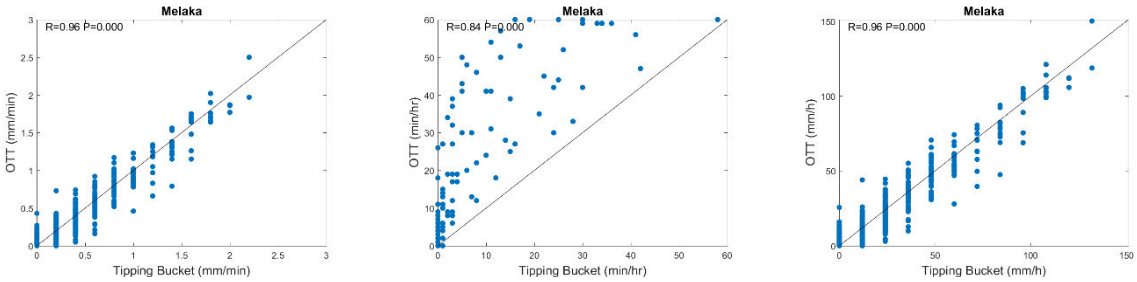
Full record

(a) **(b)** **(c)**



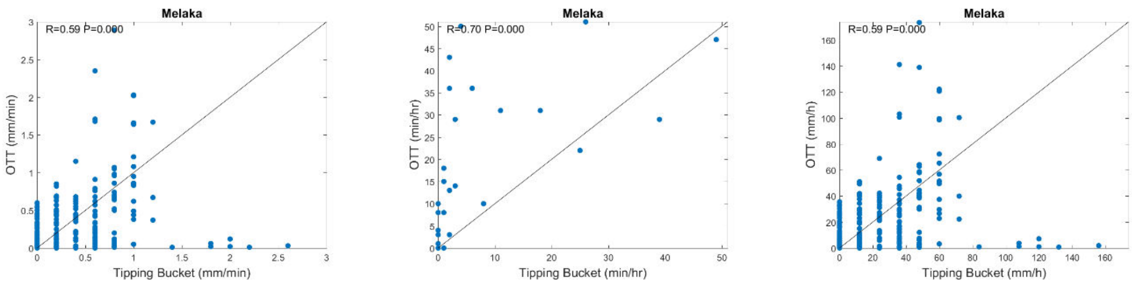
Northeast Monsoon

(d) **(e)** **(f)**



Inter-monsoonal period

(g) **(h)** **(i)**



Southwest Monsoon

(j) **(k)** **(l)**

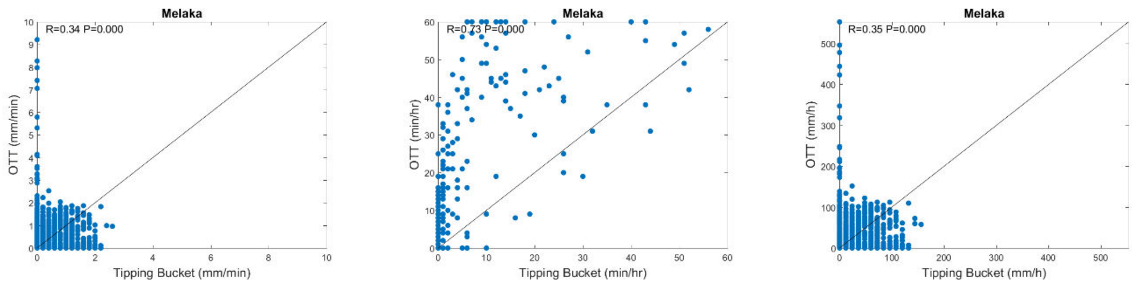


Figure 4.17. Comparison of rainfall amount, duration and rainfall intensity from OTT against reference tipping bucket for different measurement periods at Melaka station. The correlation, R and p-values are shown at the upper left corner.

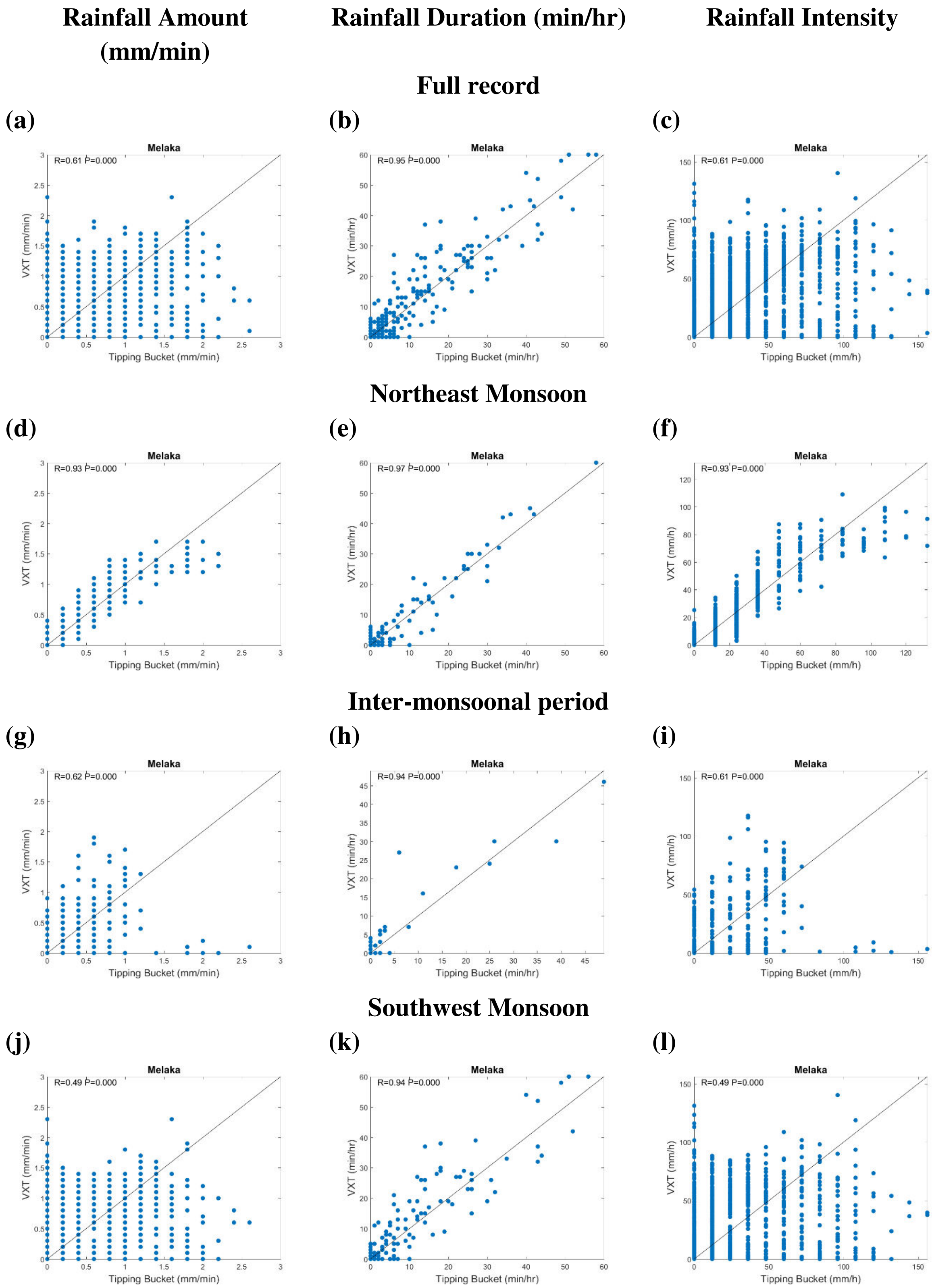


Figure 4.18. Comparison of rainfall amount, duration and rainfall intensity from VXT against reference tipping bucket for different measurement periods at Melaka station. The correlation, R and p-values are shown at the upper left corner.

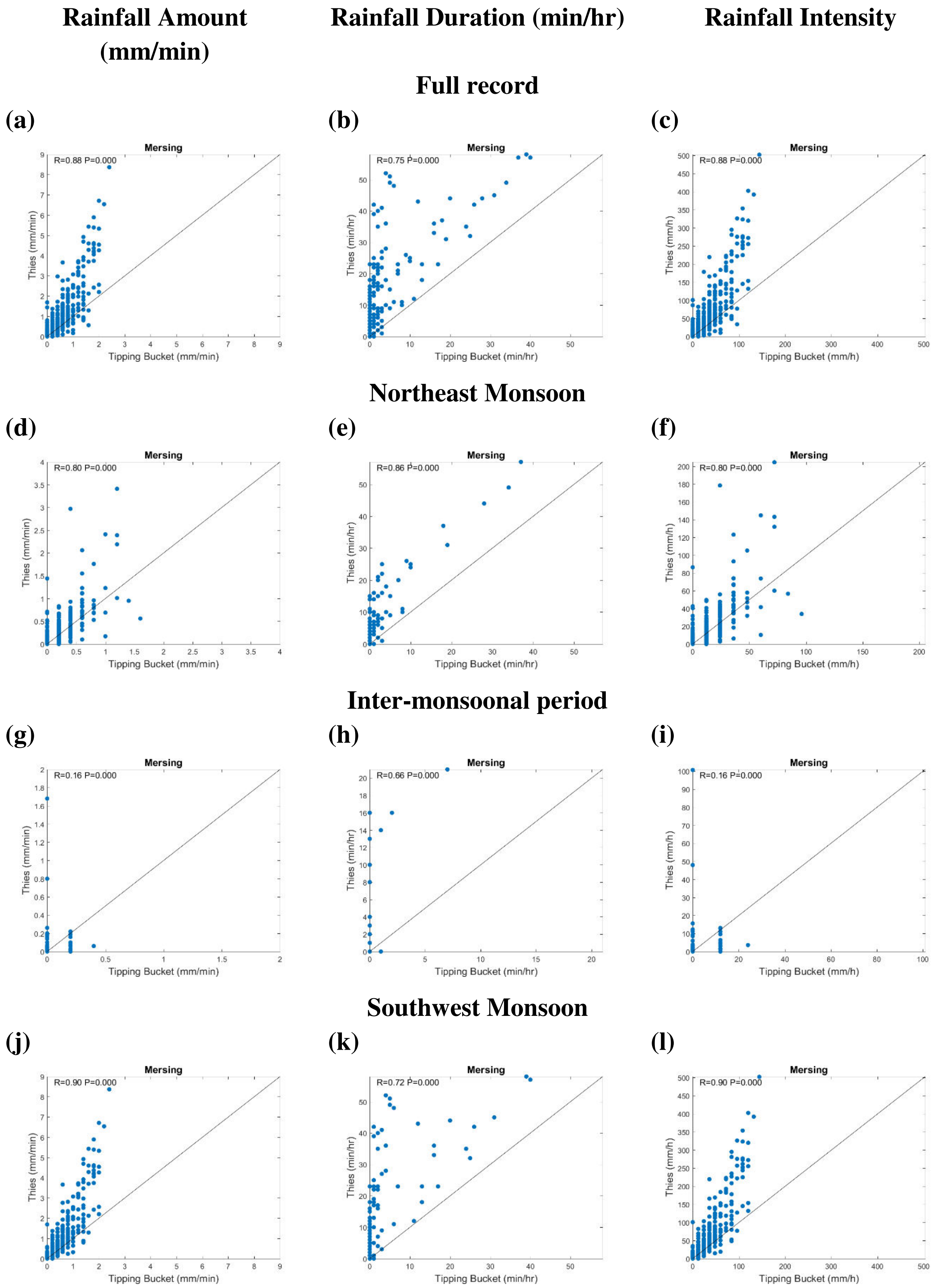
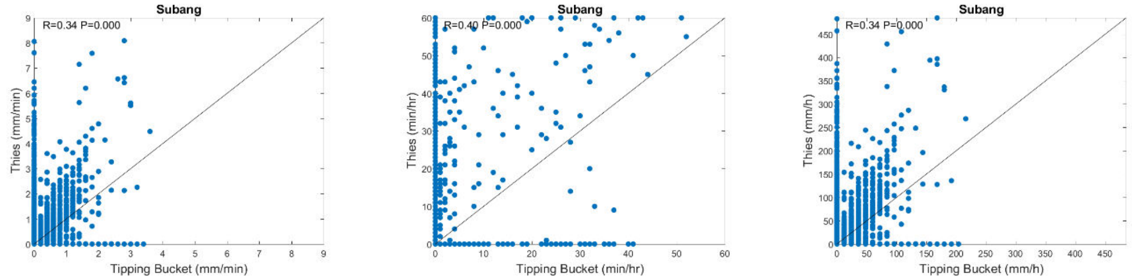


Figure 4.19. Comparison of rainfall amount, duration and rainfall intensity from Thies against reference tipping bucket for different measurement periods at Mersing station. The correlation, R and p-values are shown at the upper left corner.

Rainfall Amount (mm/min) | **Rainfall Duration (min/hr)** | **Rainfall Intensity**

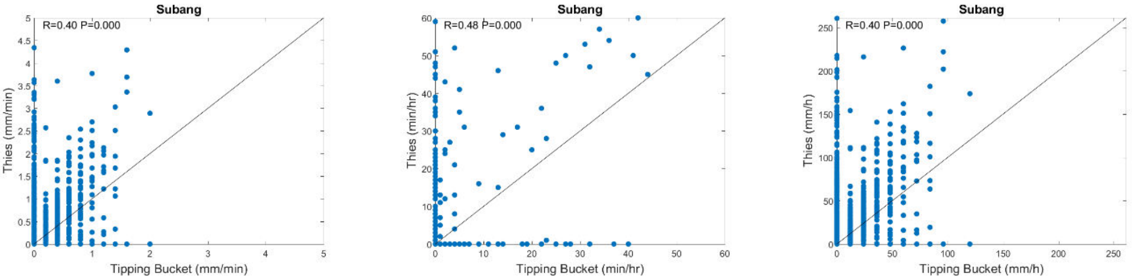
Full record

(a) **(b)** **(c)**



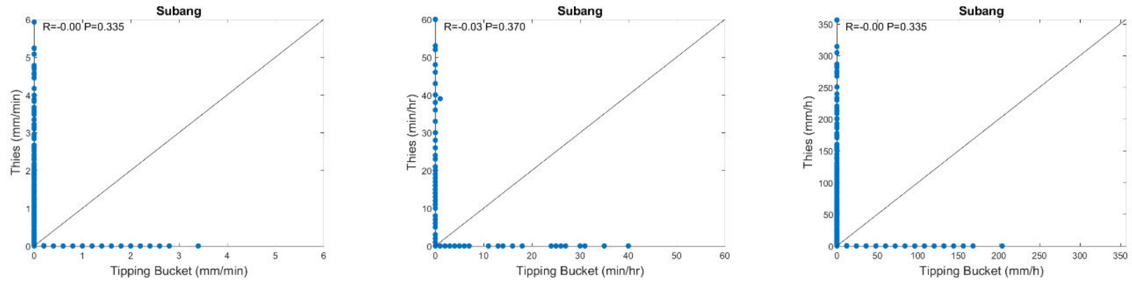
Northeast Monsoon

(d) **(e)** **(f)**



Inter-monsoonal period

(g) **(h)** **(i)**



Southwest Monsoon

(j) **(k)** **(l)**

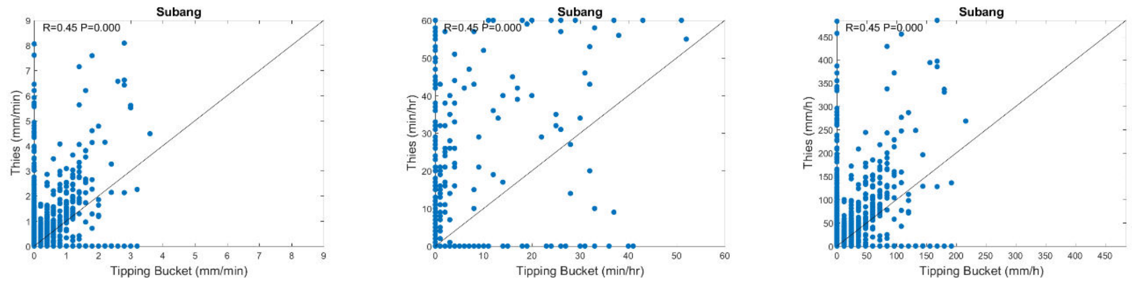


Figure 4.20. Comparison of rainfall amount, duration and rainfall intensity from Thies against reference tipping bucket for different measurement periods at Subang station. The correlation, R and p-values are shown at the upper left corner.

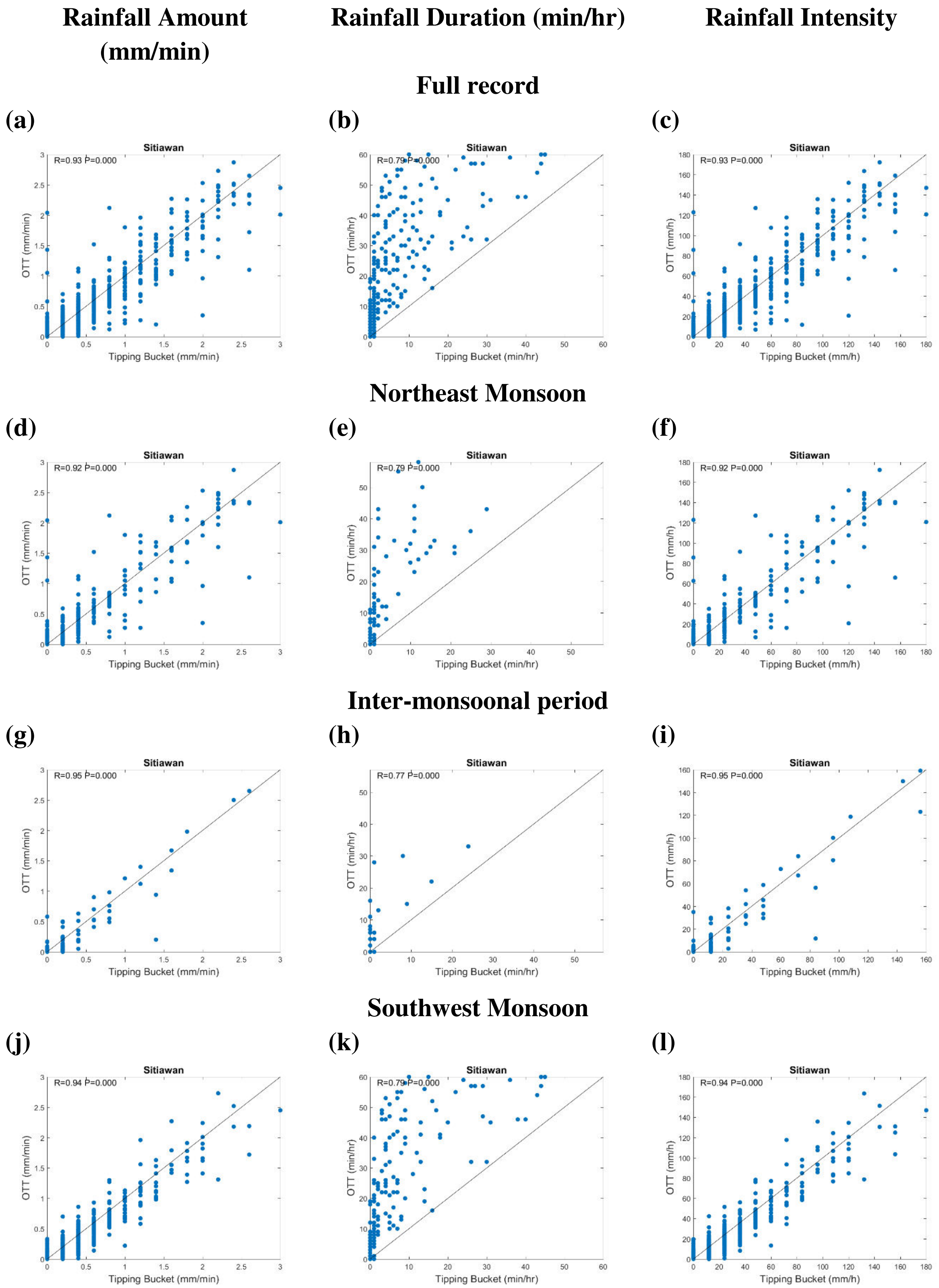


Figure 4.21. Comparison of rainfall amount, duration and rainfall intensity from OTT against reference tipping bucket for different measurement periods at Sitiawan station. The correlation, R and p-values are shown at the upper left corner.

Figure 4.22-4.24 depict the frequency distribution of rainfall amount, duration and intensity for each instruments along the measurement campaign at all stations. OTT, Thies and VXT generally are more sensitive in measuring the rainfall in the lighter rainfall events with high occurrence in rainfall amount less than 0.2mm/min. No rainfall less than 0.2mm.min was recorded by tipping bucket due to its lower resolution. As the result, more occurrence on the rainfall amount 0.2 mm recorded by tipping bucket, compared to other sensors. Similar features were found in Figure 4.24. High occurrences in rainfall intensity less 12 mm/hr were recorded with respect to those from tipping bucket. On the other side, Tipping bucket recorded relatively high occurrence in rainfall intensity 12 mm/hr. From Figure 4.22, it was found that Thies recored higher rainfall than other sensors and reference tipping bucket rain gauges for rainfall more than 2.5 mm/min. Overall, the result from Melaka has shown that OTT are most sensitive to light rainfall, followed by Theis and VXT. VXT presented the closer match the reference tipping bucket measurement.

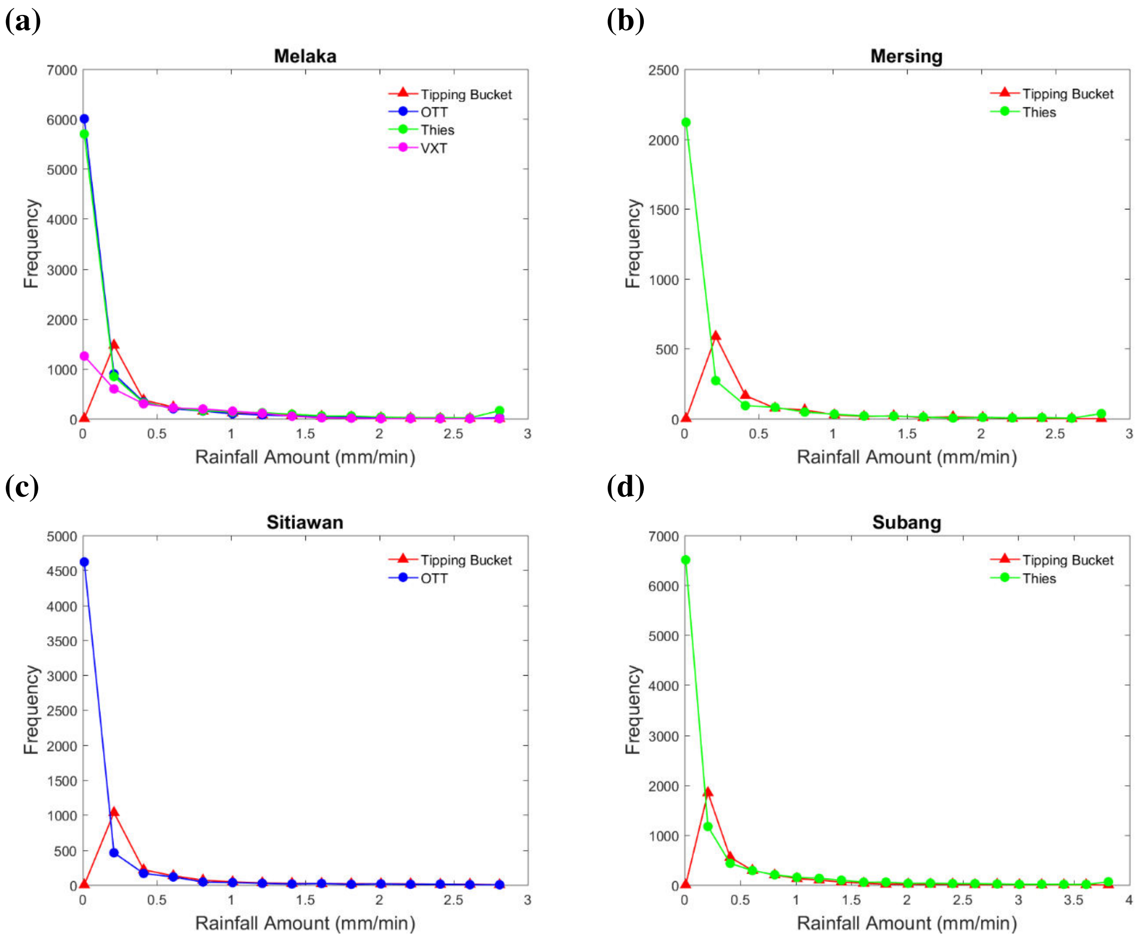


Figure 4.22. Rainfall amount of each instrument against reference tipping bucket for the full record of measurement campaign at (a) Melaka, (b) Mersing, (c) Sitiawan and (d) Subang.

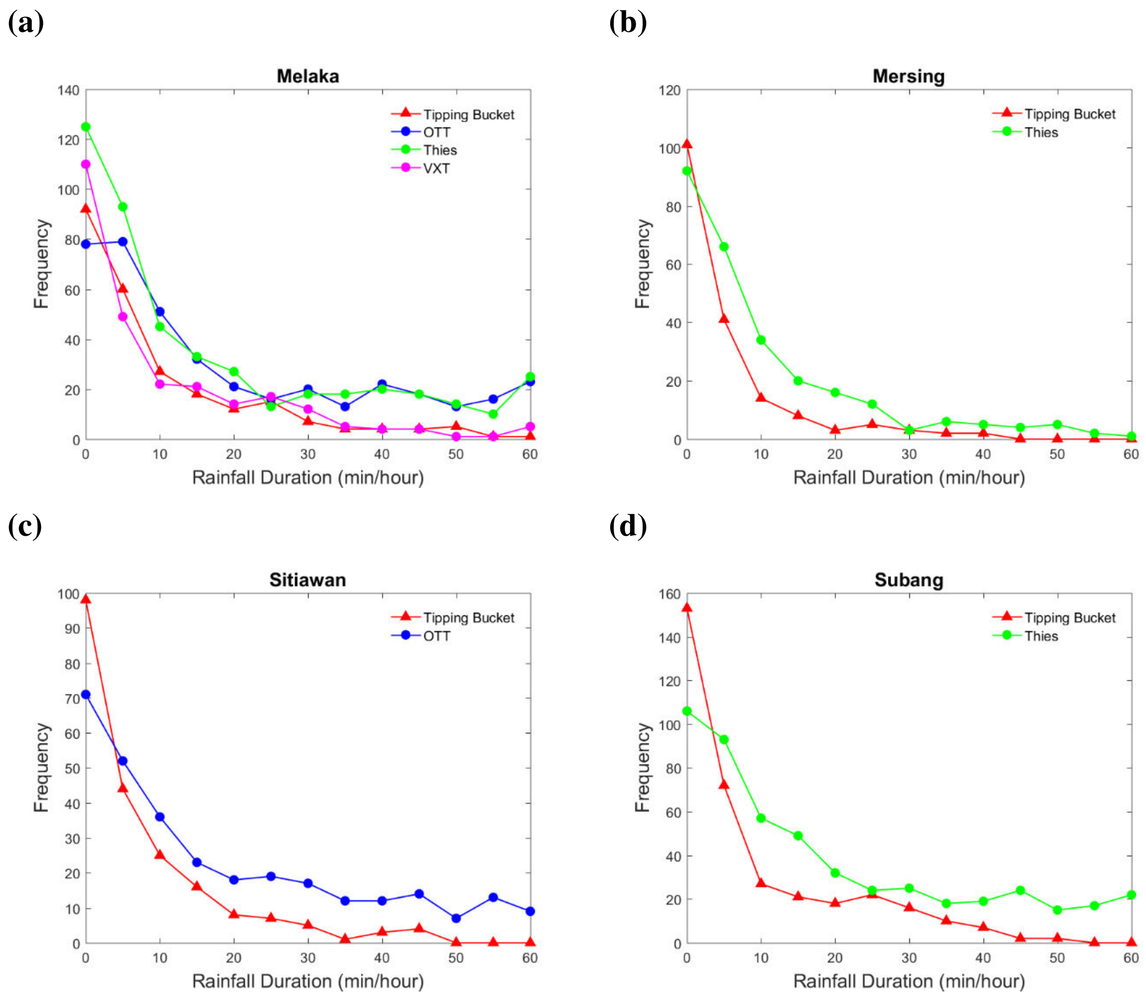


Figure 4.23. Rainfall duration of each instrument against reference tipping bucket for the full record of measurement campaign at (a) Melaka, (b) Mersing, (c) Sitiawan and (d) Subang.

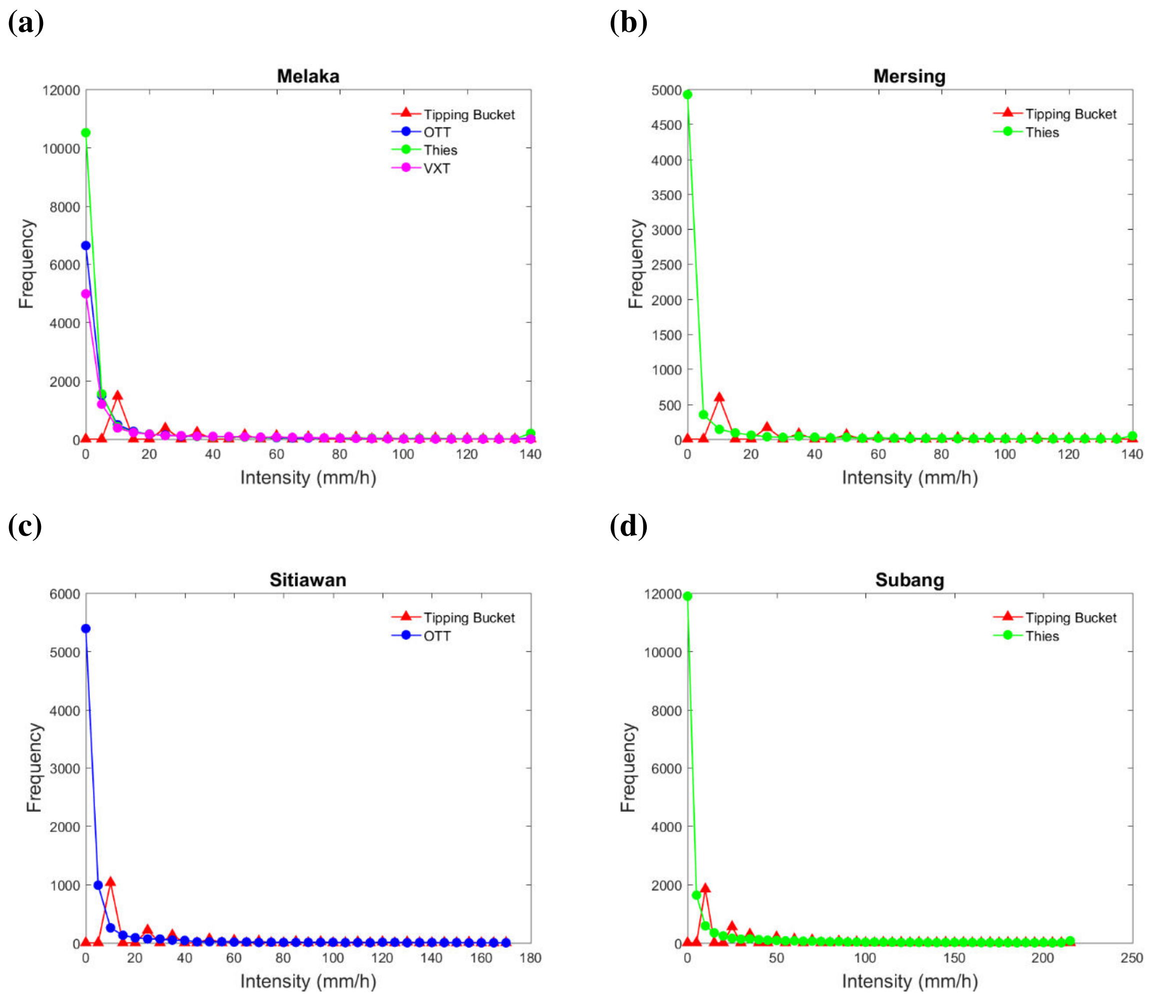


Figure 4.24. Rainfall duration of each instrument against reference tipping bucket for the full record of measurement campaign at (a) Melaka, (b) Mersing, (c) Sitiawan and (d) Subang.

The evolution of minute-by-minute rainfall amount and intensity of each instrument for measurement on 19th February 2016, starting from hour 21:00 to 22:00 at Melaka are shown in Figure 4.25 and 4.26. Once again, the rainfall amount and intensity recorded by Thies are relatively higher compared to other instruments, especially in the heavy rainfall event between 21:08-21:20. These figures are further proved that the differences of rainfall between Thies and reference tipping bucket rain gauges increase as the rainfall intensity increases. Rainfall measurement made by OTT and VXT presented a better agreement to those measured by tipping bucket. From Figure 4.25 and 4.26, tipping bucket was not able to capture the rainfall amount at the beginning of the rainfall event, before the rainfall amount reached 0.2 mm/min. This is mostly due to the lower resolution of tipping bucket, that is 0.2

mm/min or 12mm/hr. Tipping bucket rain gauge takes a little while of time to fill one tip of its compartment bucket with water droplet during rainfall occurs. Hence, tipping bucket is unable to detect rainfall event with rainfall amount less than 0.2 mm/min during the light rainfall episode. This is also the cause that resulting much less rainfall duration recorded by tipping bucket with respect to other instrument.

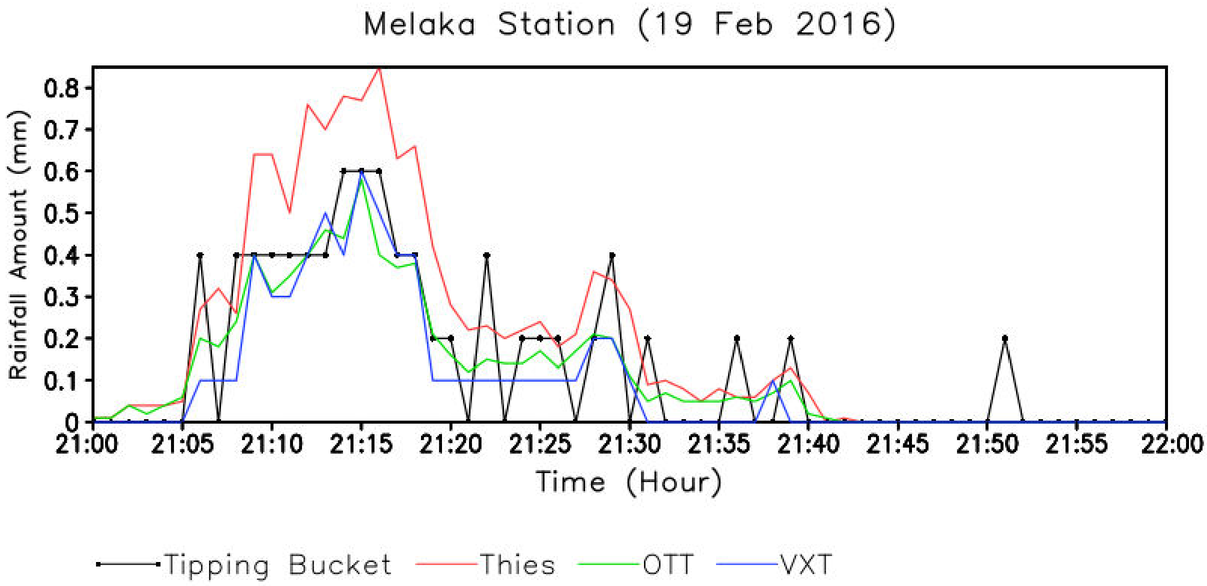


Figure 4.25. The evolution of minute-by-minute rainfall amount of each instrument for measurement on 19th Febraury 2016, from 21:00 to 22:00 at Melaka station.

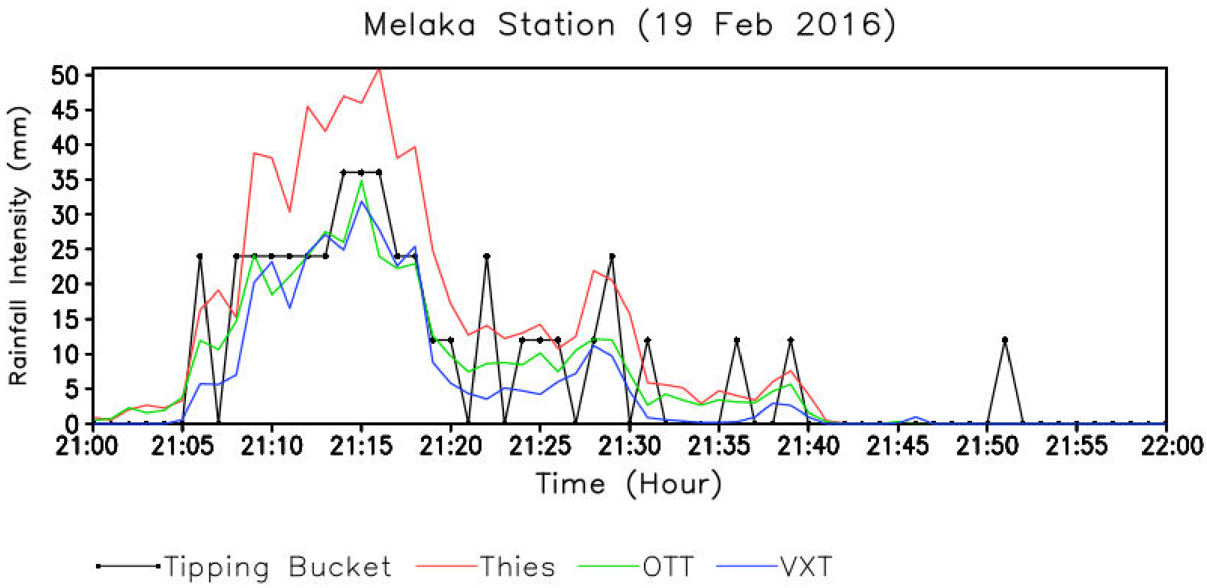


Figure 4.26. The evolution of minute-by-minute rainfall intensity of each instrument for measurement on 19th Febraury 2016, from 21:00 to 22:00 at Melaka station.

5.0 SUMMARY

This report present the performance of OTT PARSIVEL disdrometer, Theis Laser Disdrometer (Theis) and Vaisala Weather Transmitter (VXT) in comparison with tipping bucket rain gauge as a reference in measuring the rainfall amount. Seven months parallel rainfall measurement were conducted at five different locations. Prior to the comparison analysis, data return from each instrument were computed for every month and data with missing values more than 5% of the total data have been excluded from the descriptive analysis.

In general, the rainfall amount and intensity recorded by Thies are relatively higher compared to other instruments, especially in the heavy rainfall events. The differences of rainfall between Thies and reference tipping bucket rain gauges increase as the rainfall intensity increases. Rainfall amount and intensity made by OTT and VXT presented a better agreement to those measured by tipping bucket. OTT, Thies and VXT generally are more sensitive in measuring the rainfall amount in the lighter rainfall events, especially in the event of rainfall amount less than 0.2 mm/min due to their higher resolution. Apparently, the higher resolution also causing OTT and Thies measured higher rainfall duration with respect to reference tipping bucket rain gauge. Overall, the result from Melaka shows that OTT is most sensitive to light rainfall, followed by Theis and VXT. VXT presented the closer match to the reference tipping bucket measurement.

Although tipping bucket is unable to measure rainfall intensity that is less than 12 mm/hr, its still able to measure the daily rainfall intensity effectively and comparable to OTT and VXT, such as those shown in Melaka station. Therefore, the tipping bucket that currently being used is reliable especially for operational purpose and climate study.

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APPENDIX A

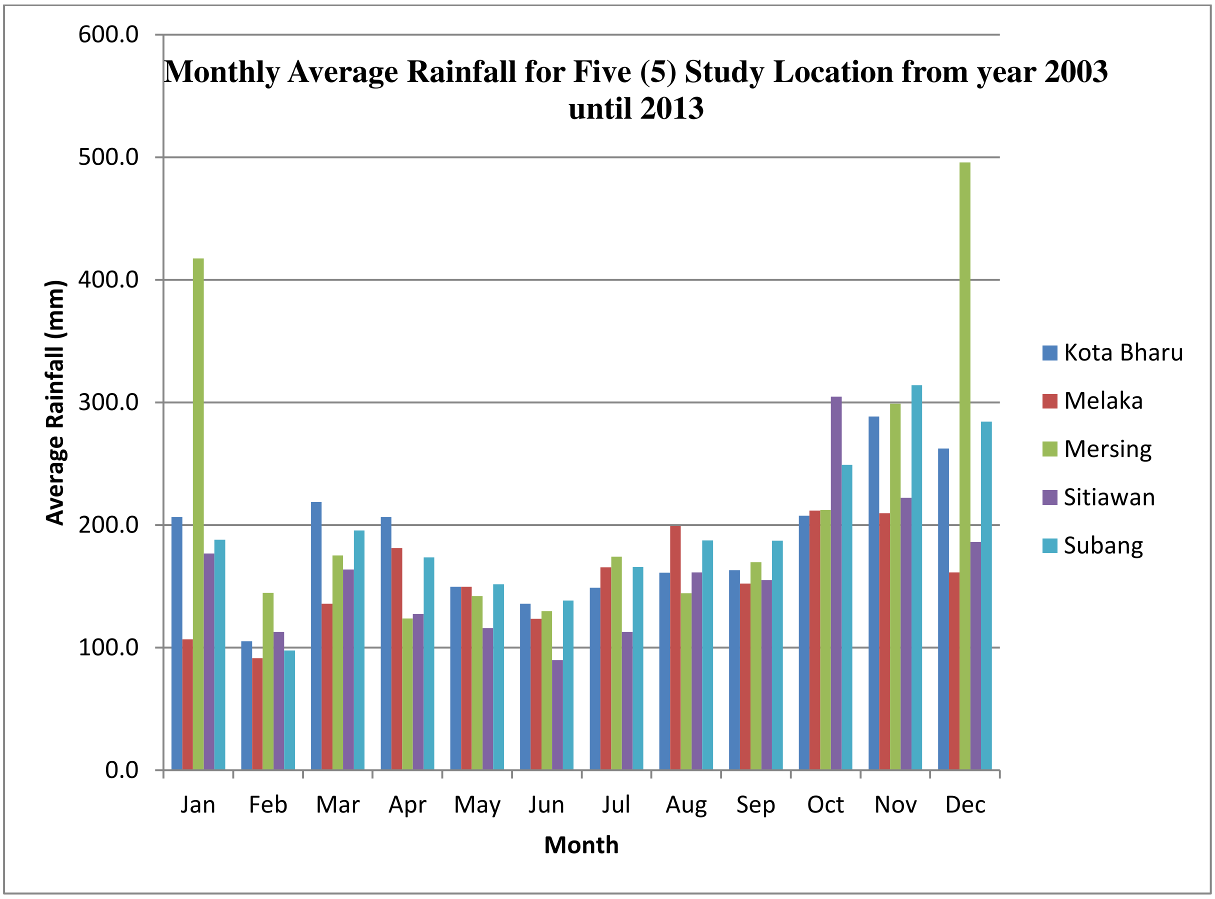
MONTHLY AVERAGE RAINFALL OF FIVE STUDY LOCATION

(FROM YEAR 2003 UNTIL 2013)

Table A : Monthly Average Rainfall from year 2003 until 2013

No	Selected station	Monthly Average Rainfall (mm) from year 2003 until 2013											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Kota Bharu	206.3	105.3	218.7	206.6	149.7	135.6	148.7	161.0	163.1	207.4	288.5	262.4
2	Melaka	106.7	91.2	135.6	181.1	149.6	123.5	165.5	199.0	152.2	211.6	209.6	161.2
3	Mersing	417.3	144.7	175.1	123.7	142.0	129.8	174.2	144.2	169.7	212.3	298.8	495.8
4	Sitiawan	176.7	112.7	163.6	127.4	115.8	89.7	112.8	161.3	155.1	304.5	222.1	186.2
5	Subang	188.0	97.5	195.4	173.5	151.6	138.4	165.8	187.5	187.3	248.9	314.1	284.3

Source : National Climate Centre, Malaysian Meteorological Department



APPENDIX B

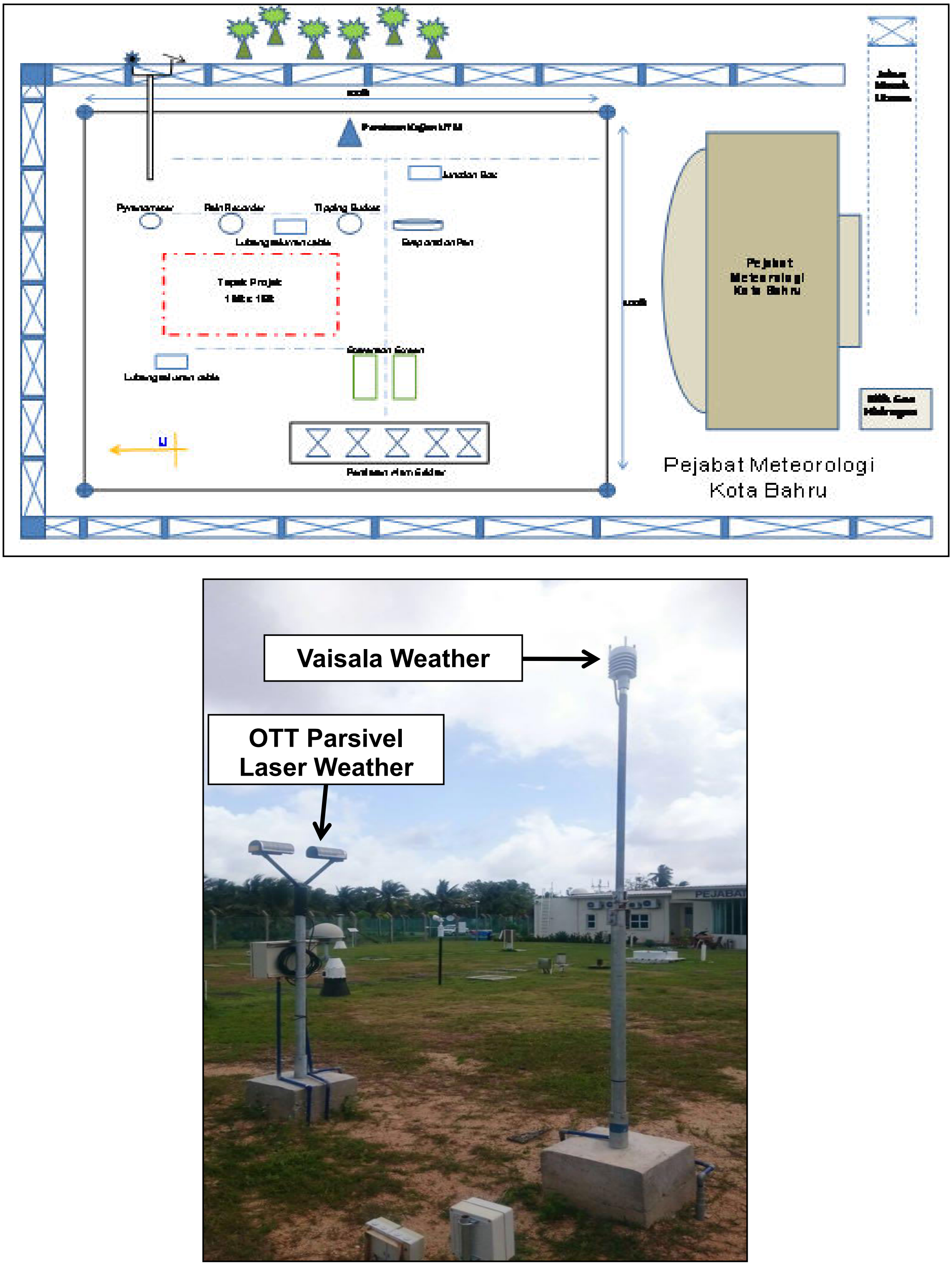


Figure B1. The Vaisala Weather Transmitter WXT520 and OTT Parsivel Laser Weather Sensor in Kota Bharu Meteorological Station site.

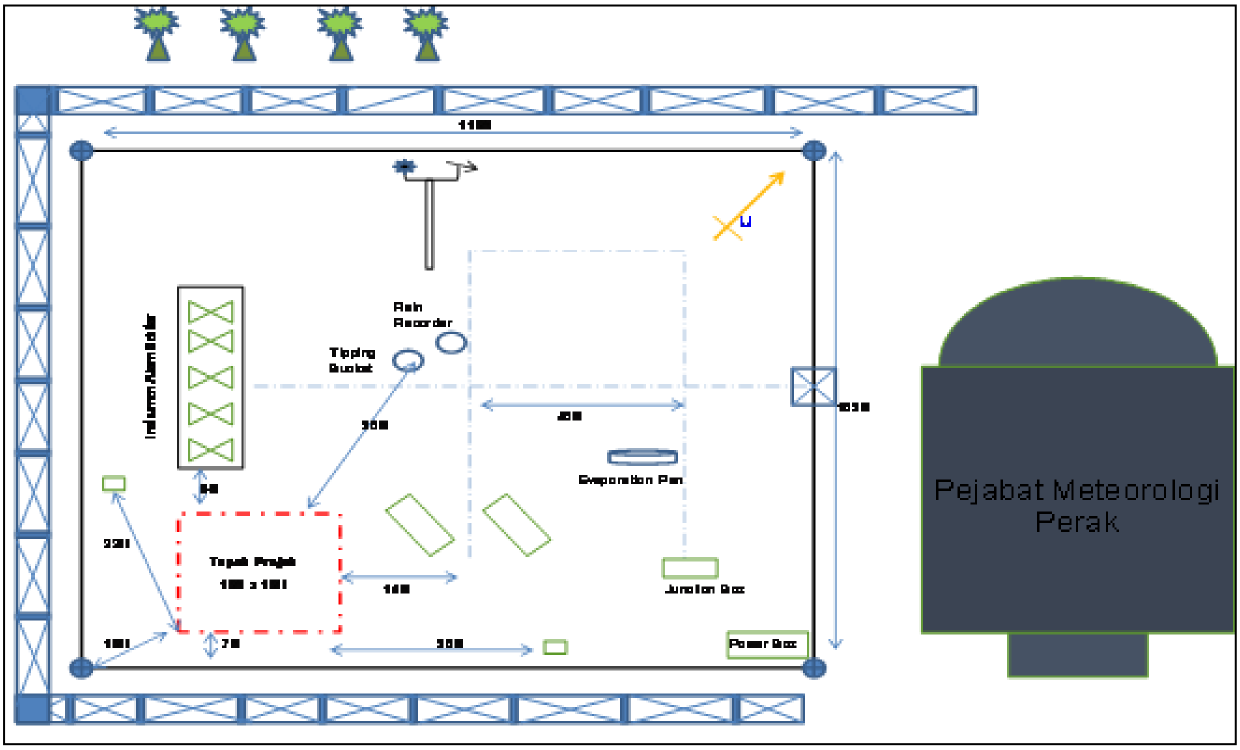
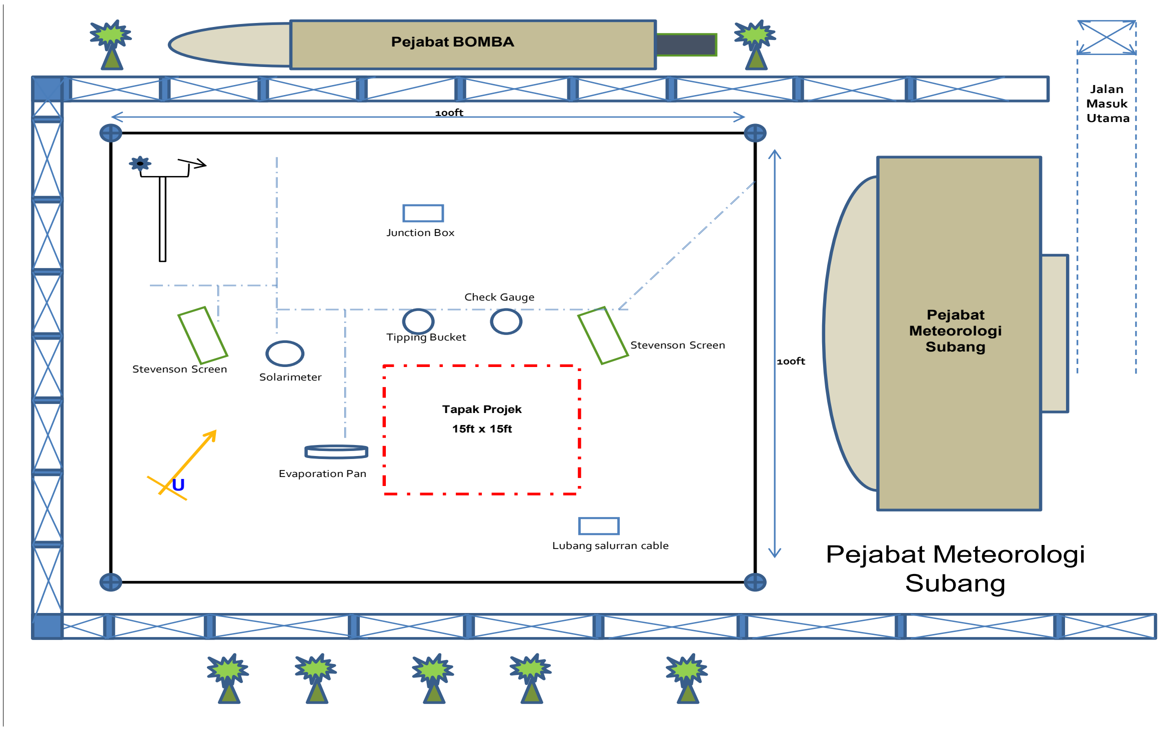


Figure B2. OTT Parsivel Laser Weather Sensor in Sitiawan Meteorological Station site.



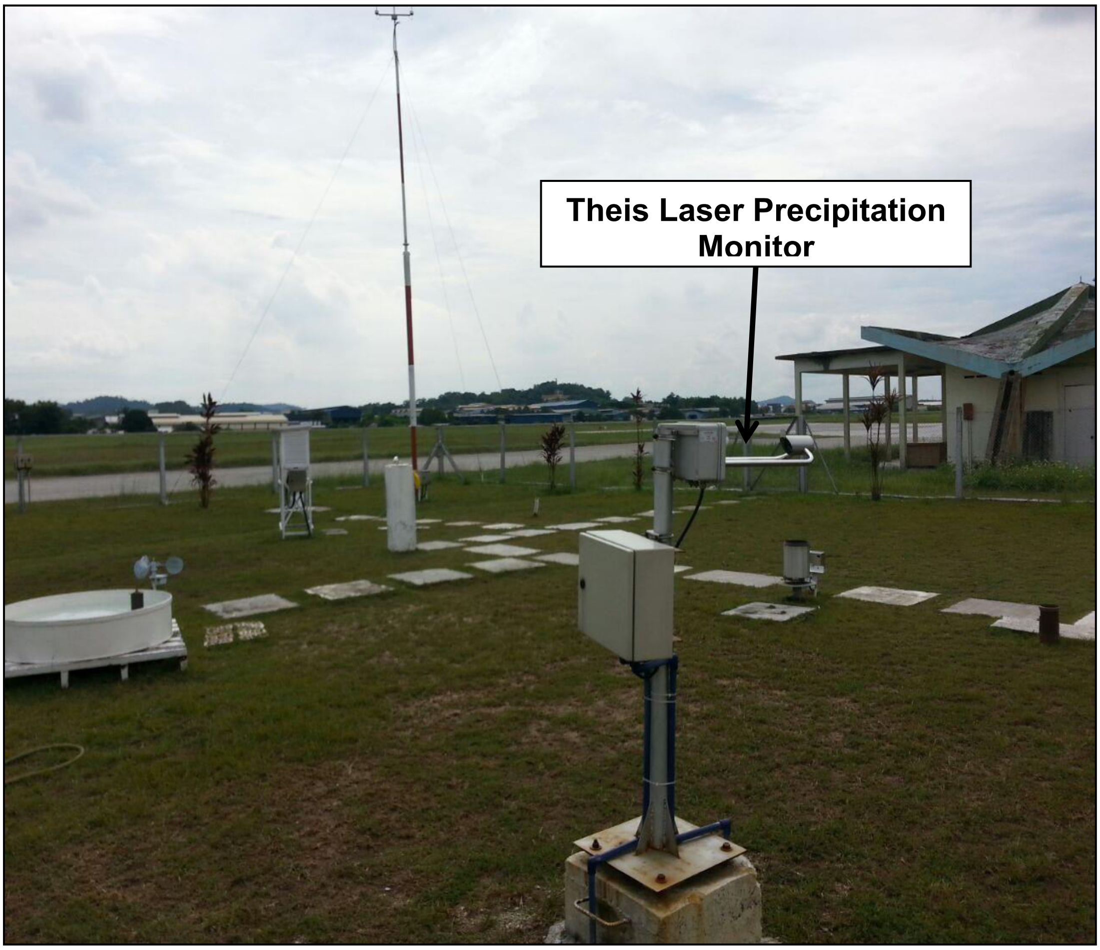
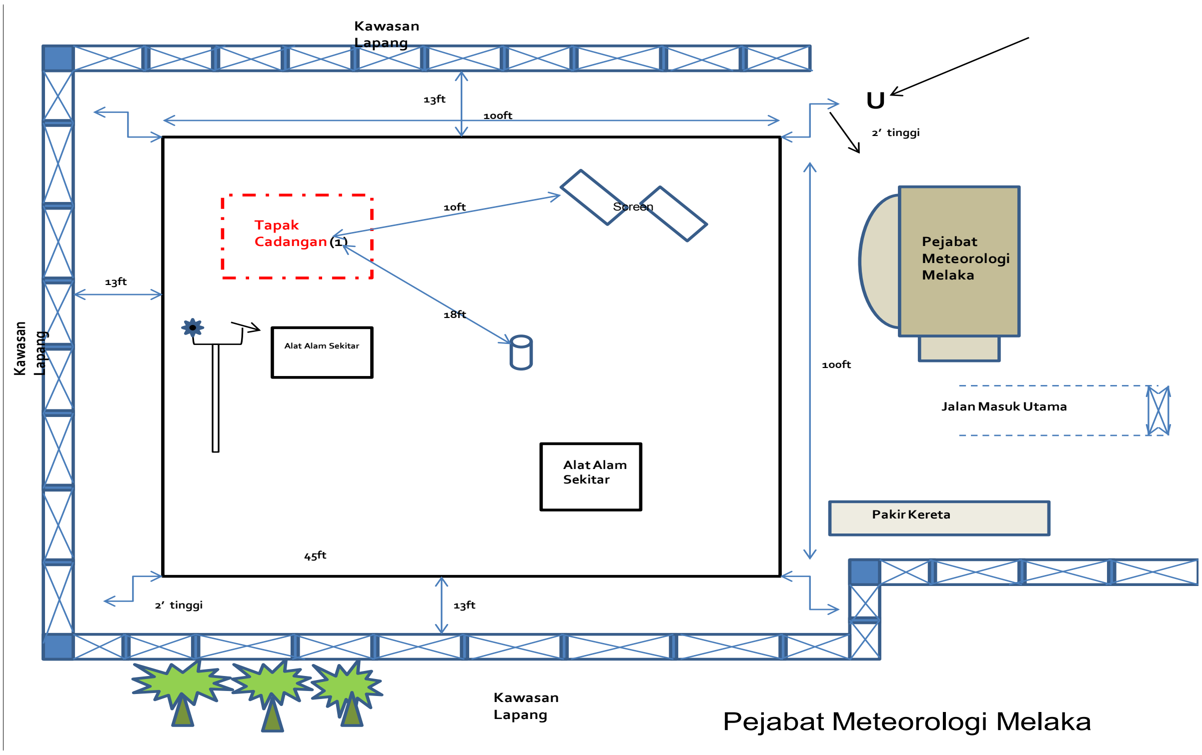


Figure B3. The Theis Laser Precipitation Monitor in Subang Meteorological Station site.



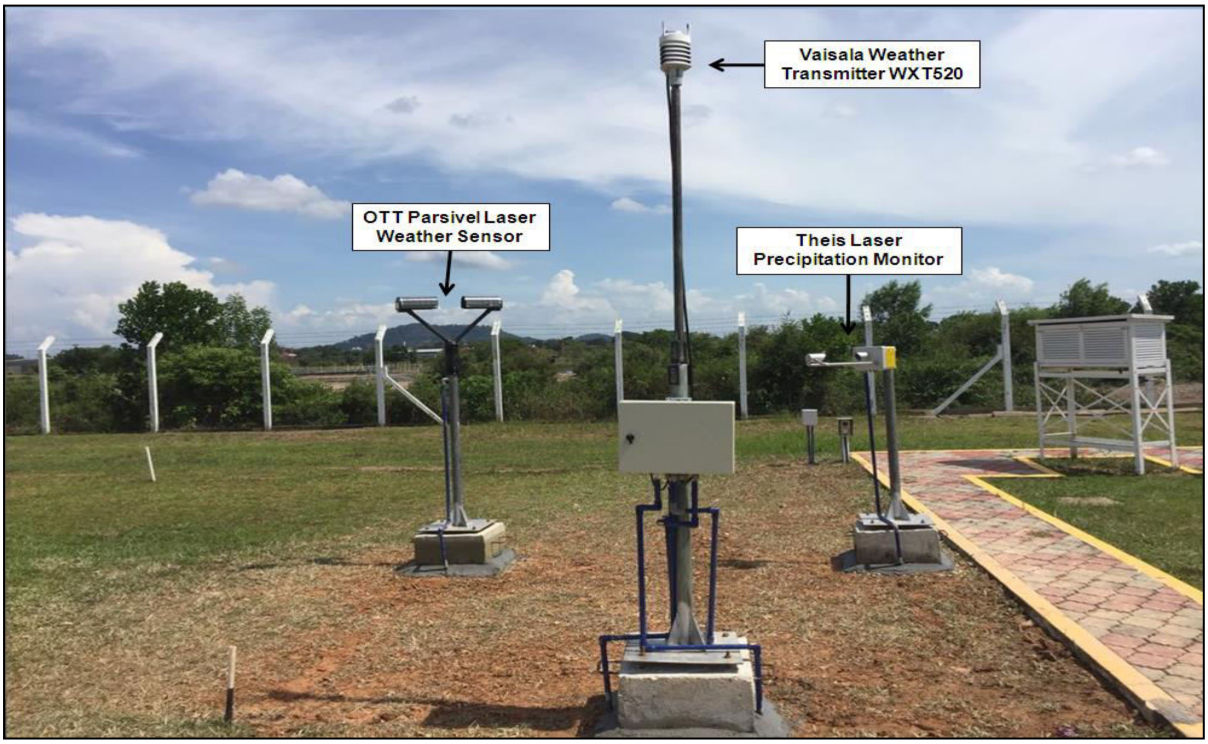


Figure B4. Overview of the three instruments (OTT Pasrivel Laser Weather Sensor, Theis Laser Precipitation Monitor and Vaisala Weather Transmitter) in Melaka Meteorological Station site.

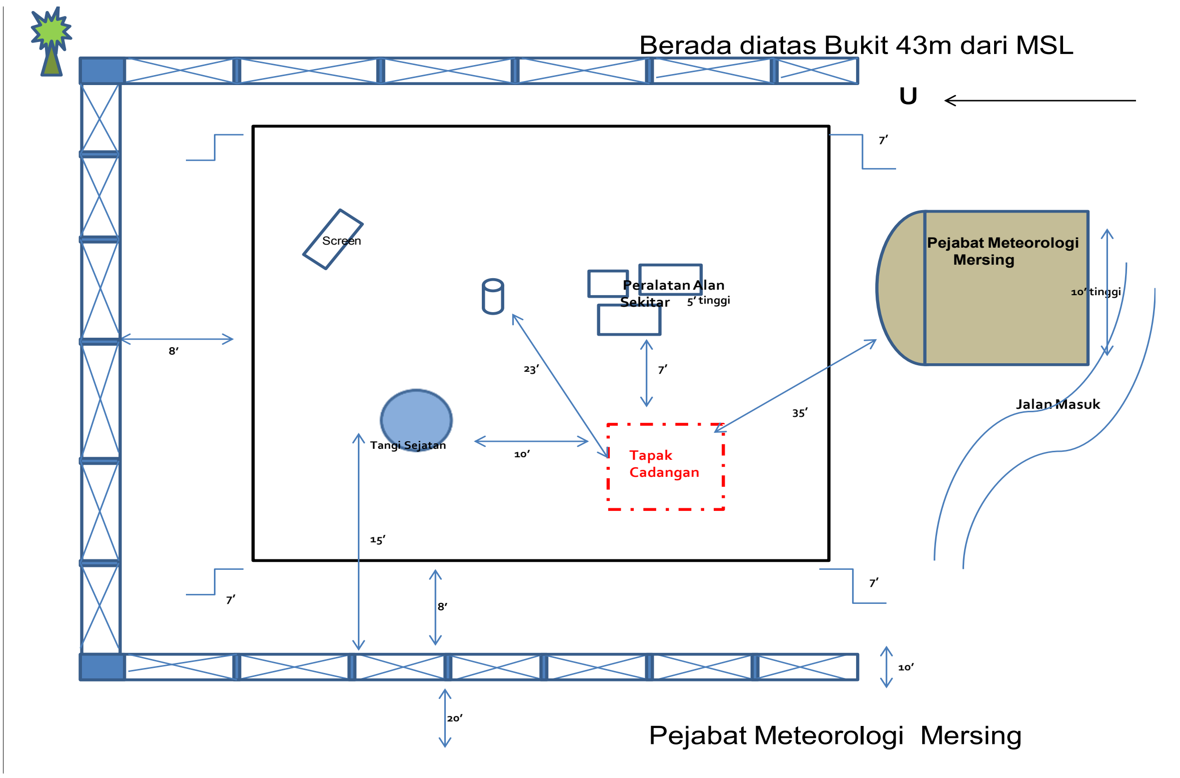


Figure B5. The Theis Laser Precipitation Monitor in Mersing Meteorological Station site.

APPENDIX C

<table>
<tr><th>Rainfall Amount (mm/min)</th><th>Rainfall Duration (min/hr)</th><th>Rainfall Intensity</th></tr>
<tr><td colspan="3">Full record</td></tr>
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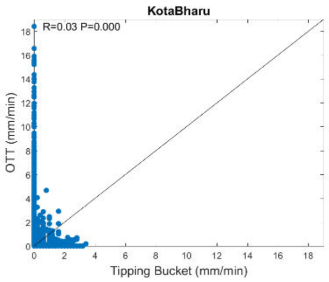
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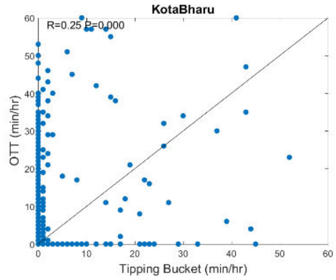
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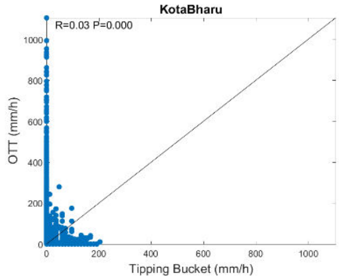
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<tr><td colspan="3">Northeast Monsoon</td></tr>
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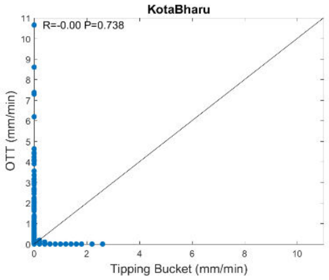
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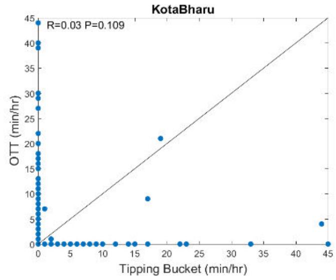
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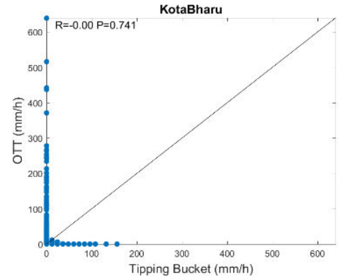
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<tr><td colspan="3">Inter-monsoonal period</td></tr>
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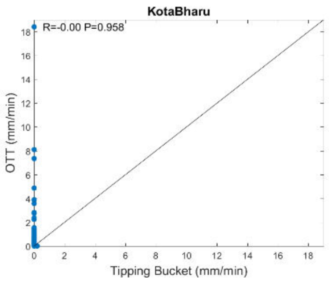
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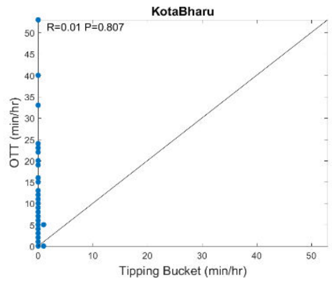
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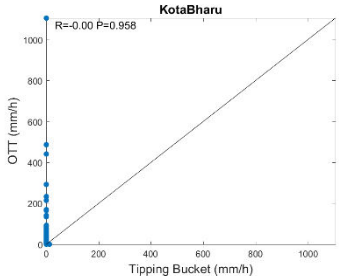
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<tr><td colspan="3">Southwest Monsoon</td></tr>
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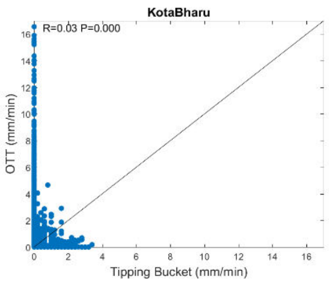
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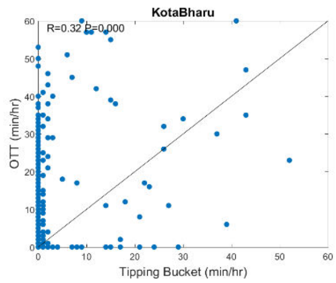
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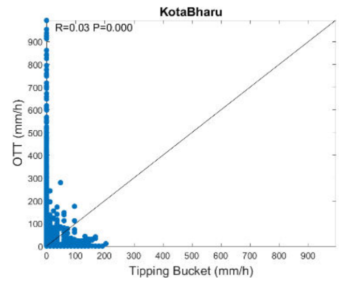
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Figure C: Comparison of rainfall amount, duration and rainfall intensity from OTT against reference tipping bucket for different measurement periods at Kota Bahru station**.**