

Monitoring the variability of precipitable water vapor over the Klang Valley, Malaysia during flash flood

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Abstract. Klang Valley is a focal area of Malaysian economic and business activities where the local weather condition is very important to maintain its reputation. Heavy rainfalls for more than an hour were reported up to 40 mm in September 2013 and 35 mm in October 2013. Both events are monitored as the first and second cases of flash flood, respectively. Based on these cases, we investigate the water vapor, rainfall, surface meteorological data (surface pressure, relative humidity, and temperature) and river water level. The precipitable water vapor (PWV) derived from Global Positioning System (GPS) is used to indicate the impact of flash flood on the rainfall. We found that PWV was dropped 4 mm in 2 hours before rainfall reached to 40 mm and dropped 3 mm in 3 hours before 35 mm of rainfall in respective cases. Variation of PWV was higher in September case compared to October case of about 2 mm. We suggest the rainfall phenomena can disturb the GPS propagation and therefore, the impact of PWV before, during and after the flash flood event at three selected GPS stations in Klang Valley is investigated for possible mitigation in the future.

1. Introduction

Klang Valley is a focal area of Malaysia where many activities are located and local weather condition plays an important role. Information on weather variability has a significant effect on economic activities, including communications, services and utilities as well as the local community [1]. As Klang Valley is the main economic area, it is very upsetting for the area to be affected by flash flood every year. Hence, more studies are needed to be carried out to provide basic information in setting up a mitigation plan against the disaster. National Oceanic and Atmospheric Administration (NOAA) has defined flash flood occurring less than 6 hours is a result of excessive rainfall within a short period of time while Department of Irrigation and Drainage (DID) Malaysia has defined flash flood as an unexpected flood due to heavy rainfall in local and its surrounding area. DID is monitoring flood based on daily total rainfall and river water level along nationwide river stream and have classified the water level of a particular station into four categories: normal, alert, warning and danger level depending on its cross sectional area. Daily total rainfall is also classified into 4 categories; light (1-10 mm), moderate (11-30 mm), heavy (31-60 mm) and very heavy (>60 mm). Information on local flood status is currently being spread online through an integrated system that monitors river water level and total daily rainfall.

Several studies on the hydrographical factor such as [2] were carried out but studies on the meteorological component need to be improvised [3]. Storm water Management and Road Tunnel



(SMART) tunnel was developed to solve issues on flash flood and peak traffic jam hours in the Klang Valley. However, this system has become less effective due to uncontrolled development and economic activities in the area. Rapid development of building construction and public facilities may cause changes in meteorological and geological of a focal area [4]. As of now, Global Positioning System (GPS) Meteorology is widely used in predicting weather nowcasting and in the study extreme weather events such as severe flood, storm and typhoon. A research in China [5] during a 2-day observations found that the trend of precipitable water vapor (PWV) from GPS is high before heavy rainfall.

The main purpose of this study is to monitor the variability GPS PWV, total daily rainfall and surface meteorological data during short-term local weather nowcasting. According to [6] and [7], variation of GPS PWV in Peninsular Malaysia is highly correlated with daily total rainfall. Two incidents of flash flood in September and October 2013 which occurred during an inter-monsoon were investigated.

2. Methodology

2.1. Dataset and Location

The main parameters used in this study were GPS and meteorological data set. GPS data was supplied by Department of Survey and Mapping Malaysia (DSMM) via RTKnet website and meteorological dataset (pressure, mean surface temperature, relative humidity) were obtained from Malaysia Meteorological Department (MMD) and downloaded from the flight-meteorology website (<http://www.wunderground.com>). Supporting dataset consists of total daily rainfall and water level was obtained via *infobanjir* website developed by DID. This study considered all DID stations located along the Klang River within the Federal Territories of Kuala Lumpur. Figure 1 showed the location of GPS stations around incident area, which located less than 60 km distance and tabulated in details in Table 1.

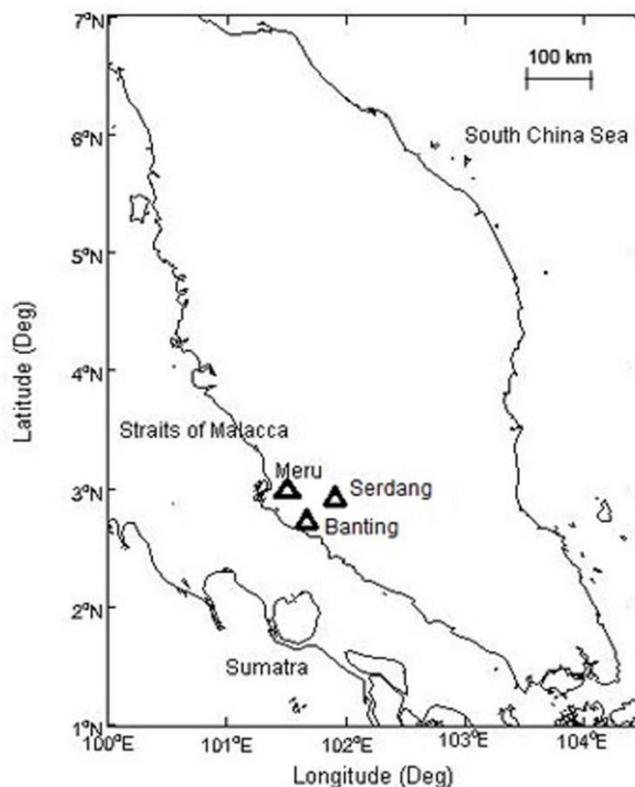


Figure 1. Location of GPS stations.

The Tropical Rainfall Measuring Mission (TRMM) precipitation data archive was used to find out the association of accumulated precipitation and rainfall. Data was freely obtained from <http://gdata1.sci.gsfc.nasa.gov>, which limited to 3 hours daily data measurement. Data was selected over Peninsular Malaysia within latitude of 0°N to 8°N and longitude of 99°N to 105°N.

Table 1. GPS coordinates and distance from point of incident.

GPS Station	Latitude (Deg)	Longitude (Deg)	Height (m)	Distance (km)
Banting (BANT)	2.83 N	101.54 E	8.83	57
Meru (MERU)	3.14 N	101.41 E	6.43	27
Serdang (UPMS)	2.99 N	101.72 E	100.38	28

2.2. Data Processing

GPS and meteorological data at every GPS station need to be cleaned before it can be processed to determine PWV. The useful noise of GPS reading as a result of neutral atmospheric delay in identifying PWV has been explained in detail by Suparta et al. [8]. The processing of PWV value is developed by using Matlab program called TroWav 2.0, which involved the regional weighted mean temperature, $T_m = 0.83663T_s + 48.103$ instead of global weighted mean temperature [9].

The main purpose of GPS station availability at particular places in Malaysia is for mapping and geodetic studies. Therefore, all GPS stations in the studied area are not equipped with meteorological sensors. As of that, meteorological parameter from interpolating technique has been used in this study [10] to determine PWV. Pattern of PWV from particular GPS station at 5 days duration during pre and post flash flood events were studied. This step also applied to study the variability of rainfall, water level and meteorological parameters. TRMM data was compared temporally and spatially to the heavy rainfall event to indicate the occurrence of flash flood.

3. Result and discussion

The daily variations of GPS PWV, total rainfall and river water level for flash flood events on 1 September and 10 October are depicted in Figure 2 and Figure 3, respectively. The 5 days mean of rainfall in September shows 2 mm higher compared in October. This September event also indicated double mean standard deviation (STD) compared to October. We also identified that the rainfall occurred every day for 5 days in September and 3 days in October.

A simple statistical analysis such as mean and STD of GPS PWV and rainfall was carried out. Both variations proved with river water level, meteorological parameters as well as TRMM precipitation image.

3.1. GPS PWV variation during flash flood in September 2013

Figure 2 showed the GPS PWV variability at three GPS stations with respect to total rainfall and water level changes. The incident of flash flood was indicated specifically at 18:00 LT that caused havoc in Klang Valley as shown by the shaded area. In the figure, phase 1, phase 2 and phase 3 are indicated for pre, during and post of flash flood events, respectively. Figure 2a showed the peak of PWV that correlated with peak of rainfall and water level. From September 2013 event, DID determined the water level into 4 levels: normal (14m), alert (17m), warning (18m) and danger (19m). By referring to the figure, the first light rainfall was recorded in late evening on 30 August due to a drop in PWV at all GPS stations (Figure 2b). It caused river water level to rise 0.5 m higher than the normal level for 2 hours (Figure 2c). A similar trend of PWV repeatedly occurred on the following day with moderate rainfall (11 mm) resulted in the rise of river water level 1.5 m over a normal level for few hours. This 9 hours of rainfall caused 3 mm drop of PWV at UPMS and BANT and 1 mm drop at MERU, but the drop in BANT station occurred earlier than in Klang and UPMS.

The next episode of rainfall that caused a flash flood event was in evening of 1 September. The rainfall was recorded to be 40 mm as a result of 6 mm PWV drop at UPMS and 2 mm PWV drop at Klang 2 hours before the heavy rainfall event. However, PWV at BANT did not show a similar trend as the PWV at UPMS and Klang. PWV at BANT was varied normally where it dropped early in the morning and became highest in the afternoon and later decreased in the evening. This phenomenon may be due to normal water evaporation from the earth's surface during sun rise and sunset. The heavy rainfall resulted in 1.5 meter rise of river water level that sustained until midnight of 1 September. This was also another factor contributed to the flash incident at flood-prone areas.

After the occurrence of heavy rainfall on 1 September, there was no rainfall recorded on 2 September except for an hour in the early morning. We found all GPS PWV reached their minimum peaks on 2 September followed by light and moderate rainfall on 3 September. It seemed the circulation of evaporation occurred on 2 September, which results in whole day rainfall on the following day. From the case of flash flood September 2013 analysis we found that the GPS PWV decreased almost 4 mm at 2 hours before heavy rainfall.

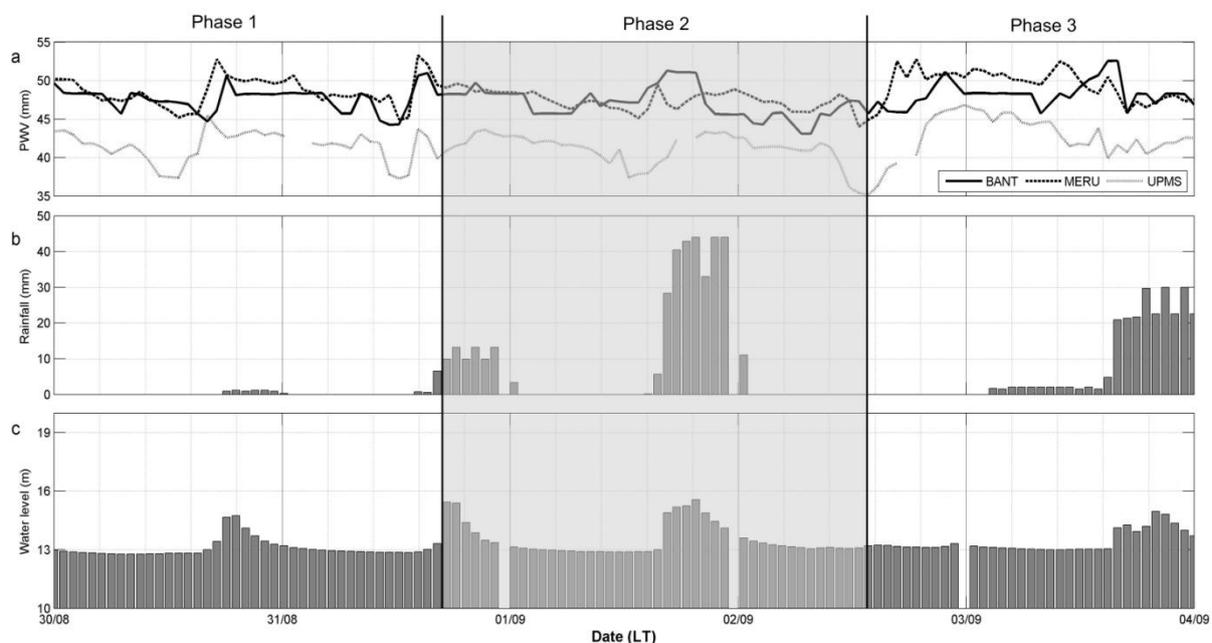


Figure 2. Variation of (a) PWV at three GPS stations, (b) rainfall and (c) river water level within 5 days from 30 August to 4 September where 1 September 2013 is flash flood event.

GPS PWV was found to be higher at MERU and UPMS within 40 hours of a flash flood event (shaded area). It was an increase of as much as 1 mm of mean GPS PWV at both stations. However, it did not happen in BANT where mean value of PWV at the same event was 1 mm lower as compared to phase 1. Mean of GPS PWV at MERU and UPMS decreased by 1 mm in phase 3 where it showed similarly before the flash flood event. It did not happen in BANT station where the mean value continuously increased by 1 mm in the following phase. Overall, GPS PWV was highest during phase of a flash flood event by 0.33 mm compared to pre and post events. Table 2 showed the mean and STD of PWV and rainfall during 5 days of pre and post flash flood events. The variation of GPS PWV was highest in UPMS during phase 1 and phase 2 followed by MERU and BANT. GPS PWV varied by less than 2 mm STD in phase 1. In phase 2, the PWV variation was recorded to be more than 2 mm and less than 3 mm compared to phase 1. It showed that GPS detected the atmospheric disturbances in phase 2 that could be a result of atmospheric water vapour and later on caused the flash flood. STD of GPS PWV decreased by 1 mm in phase 3. Individually, PWV varied the most in BANT and varied the least in UPMS.

Rainfall was recorded the highest during phase 2, which was 5 mm more in from pre event and 1 mm more in post event. The highest variation trend of rainfall was also similar to the trend of GPS PWV.

Table 2. Statistical value of GPS PWV and rainfall within 5 days observations from Figure 2.

Phase	Station		GPS		Rainfall	
	GPS	Rainfall*	Mean	STD	Mean	STD
1	Banting		47.90	1.59		
	Meru		48.00	1.70	2.09	4.21
	Serdang		41.10	1.86		
2	Banting	Jambatan	47.02	2.04		
	Meru	Petaling	48.67	2.16	7.42	15.30
	Serdang		42.32	3.16		
3	Banting		48.03	1.98		
	Meru		47.94	1.65	6.39	10.19
	Serdang		41.61	1.36		

*Rainfall data only recorded at Jambatan Petaling. All values are in mm.

3.2. GPS PWV variation during flash flood in October 2013

Another flash flood that hit Klang Valley was on 10 October after 3 hours of rainfall. Figure 3 showed the variation of GPS PWV at three GPS stations as well as total rainfall and changes of river water level as Figure 2. For October 2013 flash flood event, DID determine the water level into 4 levels: normal (24 m), alert (28 m), warning (29 m) and danger (30 m).

Similar to Figure 2, Figure 3a showed the variation of PWV at three nearest GPS stations that correlated to total rainfall and changes of river water level. PWV at UPMS recorded the lowest, while at BANT is the highest. During five consecutive days of monitoring, PWV reached a minimum peak in the afternoon with 2 minimum peaks at UPMS in the evening of 9 October. The first rainfall was recorded in the evening of 10 October as shown in Figure 3b that brought to flash flood at several parts in Klang Valley. Flash flood was reported hit over Klang Valley after 3 hours of rainfall after 1700 LT. From our observation, rainfall is occurred later after PWV dropped at all GPS stations. We identified 4 mm dropped of PWV at UPMS, while 4 mm and 9 mm dropped before rainfall at BANT and MERU, respectively. PWV at BANT and MERU dropped later than in UPMS with lead time 3 hours and 4 hours, respectively. The other 2 rainfall events were in the evening of 11 October and 12 October lead to drop the PWV at all GPS stations. The most PWV response with decreasing trend on 11 October before light rainfall can be seen at UPMS, and the least PWV was occurred at MERU. On 12 October, PWV at all GPS stations showed a decreasing trend before light rainfall with lead time of 2 hours. River water level in Figure 3c was drastically raised over warning level in the evening of 10 October, which believed causing a flash flood at the surrounding areas. The river water level then continued above the normal level on the following day and only declined to a normal level on 12 October. However, light rainfall in the evening of 12 October caused 1 m rise of river water level. Before that, we observed river water level drastically increased reaching alert level on 9 October even though no rainfall was recorded. It may be rainfall in the surrounding areas is not recorded at the Leboh Pasar DID station.

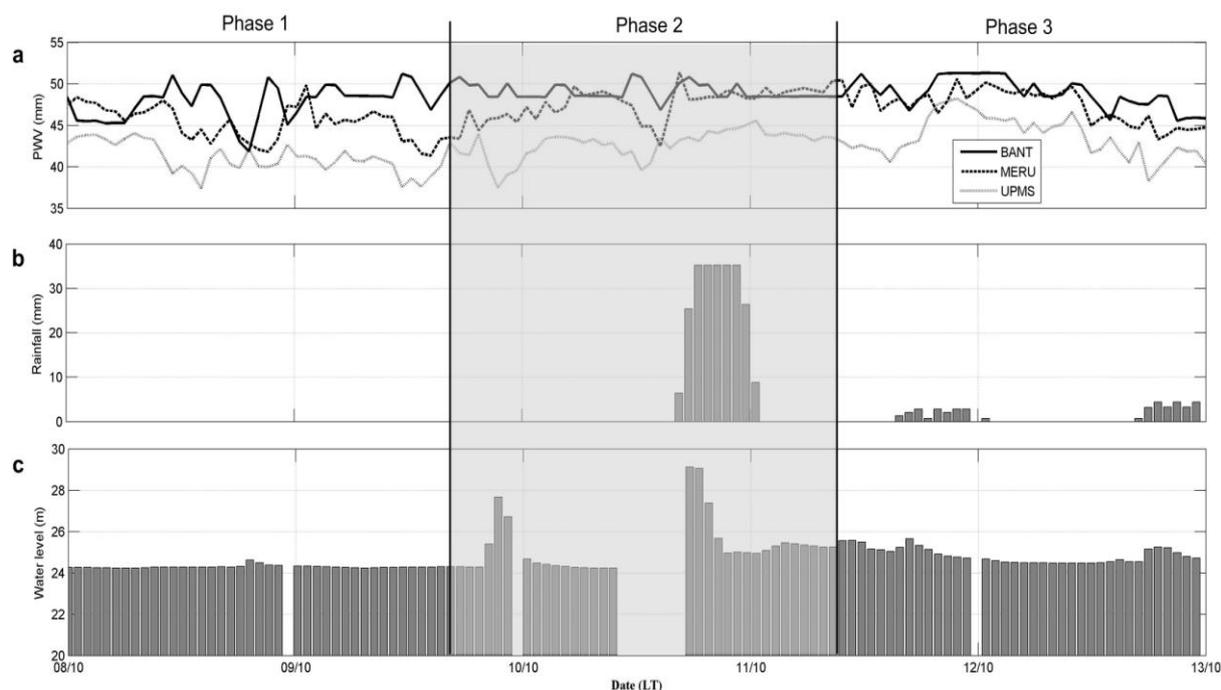


Figure 3. Variation of (a) PWV at three GPS stations, (b) rainfall and (c) river water level within 5 days of 10 October 2013 flash flood event.

As shown in Table 3, we found the mean of GPS PWV at all three stations were the highest within 40 hours (phase 2) during the event, which is 1 mm higher compared to phase 1 and phase 3, respectively. It showed phase 2 was wetter than phase 1 and phase 3 where the increasing of PWV trend (Figure 3a) in the evening of 9 October maintained at high level until morning of 12 October. The STD of PWV at every GPS station was almost 2 mm before and after the flash flood incident, but lowest in phase 2. The STD decreased 1 mm from phase 1 to phase 2 and increased 1 mm when entering phase 3. This pattern was opposite from the pattern of flash flood in September.

As mentioned before, there was no rainfall recorded in phase 1 that resulted in no variation of rainfall in this phase. The only first occurrence of rainfall in phase 2 was in the evening of 10 October, which recorded 35 mm with STD of about 13 mm. Light rainfall event repeatedly occurred in the evening of following day and another day which caused deviation of 1.52 mm.

Table 3. Statistical value of GPS PWV and rainfall within 5 days from Figure 3.

Phase	Station		GPS		Rainfall	
	GPS	Rainfall*	Mean	STD	Mean	STD
1	Banting		48.11	1.92		
	Meru		47.23	1.92	0.00	0.00
	Serdang		46.51	1.89		
2	Banting	Leboh	48.79	0.89		
	Meru	Pasar	48.80	0.89	6.11	12.57
	Serdang		48.02	0.88		
3	Banting		47.52	1.53		
	Meru		47.53	1.53	1.04	1.52
	Serdang		46.78	1.51		

*Rainfall data only recorded at Leboh Pasar. All values are in mm.

3.3. Association of PWV variation with accumulated precipitation from TRMM

From our analysis on the TRMM image specifically at latitude 2°N to 3°N and longitude 101.5°E to 200.0°E where three GPS stations are located (triangle), we found the accumulated precipitation was greatest in the evening during 1 September and 10 October flash flood event. As shown in Figure 4a, accumulated precipitation was less than 15 mm in the afternoon of 1 September. Precipitation >60 mm occurred above MERU. All GPS stations did not receive rainfall during this time until 14:00 LT. During this time, GPS stations in UPMS and BANT received 40 mm rainfall except in MERU where it received less than 20 mm rainfall or none as shown in Figure 4b. At this time (Figure 4b), North Malaysia (Kedah and Perlis) received more precipitation. For the three locations of GPS station, it is a proven that heavy rainfall was occurred in the evening on 1 September.

Figure 4c showed accumulated precipitation in the afternoon on 10 October where it was higher than 30 mm at all GPS stations. The accumulated precipitation increased more than 35 mm in the evening at almost all the GPS stations as shown in Figure 4d. It was similar to heavy rainfall recorded at this time amounting 35 mm hourly. As shown in the contour image, accumulation precipitation in October is higher compared in September. Overall in Figure 4, the accumulation precipitation within 6 hours in October was 15 mm greater compared to September. The accumulation of precipitation in September was less than 15 mm, which occurred in the afternoon. On the other hand, in these flash flood cases, the accumulated precipitation in Figure 4 was linearly correlated with the amount of GPS PWV value in Figure 2 and Figure 3.

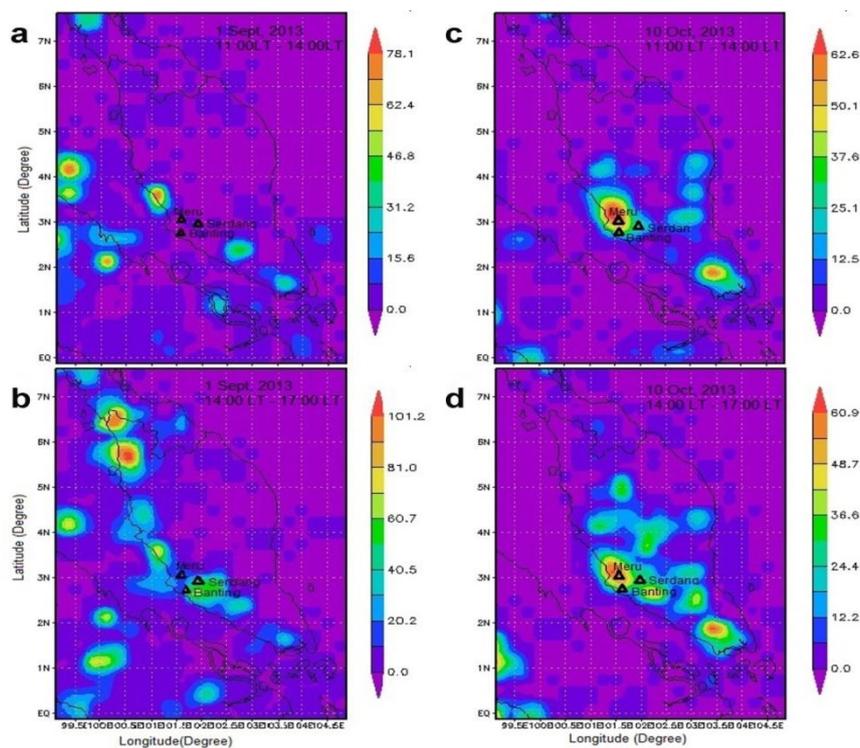


Figure 4. Accumulated precipitation (mm) from TRMM.

4. Conclusion

Monitoring the variation of GPS PWV during pre and post flash flood events over the Klang Valley in September and October 2013 flash flood was reported. These flash flood events during the inter-monsoon with heavy rainfall have been investigated by looking at the increasing trend of GPS PWV. Specifically, heavy rainfall in the evening during a flash flood can be detected earlier by looking at its decreasing trend of ~3 mm within 2 hours before the rainfall event. PWV variation was varied slowly

in the afternoon of a flash flood event. During flash flood events, PWV value in October is higher with low STD than in September, which is contrasted with the amount of rainfall (precipitation is highest). This indicated that the variation of PWV is influenced by a winter monsoon. Detail of PWV variability for country mitigation will be investigated further by considering wind properties that associates with precipitation that possibly may help to improve weather nowcasting over Klang Valley.

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