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Monitoring of GPS Precipitable Water Vapor During the Severe Flood in Kelantan

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Abstract: Problem statement: This study mainly discusses the possibility of PWV derived from GPS data for monitoring of water vapor changes during the severe flood due to heavy rainfall. There are two cases of heavy rainfall recorded during the winter monsoon in November 2009 at Kuala Krai, Kelantan. **Approach:** The first and second cases were sustained for 3 days from 4-6 November and 7 days from 18 until 24 November with recorded maximum daily rainfall more than 180 mm and 220 mm, respectively. However from the Malaysia Meteorology Department (MMD) report, only the second case was caused the severe flood. PWV and the surface meteorological data for both cases showed a significant response to the heavy rainfall. **Results:** During the severe flood, PWV was observed decreased of about 3.52 mm. **Conclusion:** We highlighted that the widespread and enormous cumulonimbus cloud cluster sheltered the area due to cold surge during the winter monsoon can cause the unnatural peak on PWV during the heavy rainfall.

Key words: GPS, precipitable water vapor, unnatural peak, winter monsoon, meteorological elements, severe flood, radar images

INTRODUCTION

Nowadays, the accurate weather information is demand due to the strong influence of the weather condition to social and economic activities (Lazo *et al*., 2011). The information is not only used in weather alert for safety reason, but the more important is for long-term planning such as Southwest Monsoon (SWM) from the end of May to September and the Northeast Monsoon (NEM) from November to March. The NEM is characterized as a major rainy season in Malaysia. Obviously, the monsoon brings vast rainfall that may cause severe floods, especially along the east coast states of Peninsular Malaysia MMD, 2011.

Malaysia is surrounded by the sea and most of the land areas are still inaccessible due to forest and hills. Therefore, oceanic rainfall and the widespread inland rainfall data are impossible with rain gauge. Thus, comparison between forecast rainfall and observations collected by randomly distributed rain gauges may produce misleading results. Although many climatologist studies show that satellite sensors can provide information on hydrological cycle, verify the short-term forecasts over marine and remote regions remains problematic (Ikai and Nakamura, 2003; Imakoa and Spencere, 2000).

Water vapor is one of an important parameter in the study of rainfall activity since the formation of clouds, fogs and precipitations depend on its condensation. In this study, we proposed to monitor the heavy rainfall occurrences associated with water vapor changes through the Precipitable Water Vapor (PWV) derived from GPS data. Current GPS receiving system promise a cost-effective for monitoring the tropospheric phenomenon on a global basis with superior temporal and spatial resolution. Therefore, the purpose of this study is to utilize the GPS data to monitor severe flood. The incident of severe flood in Kuala Krai, Kelantan during a NEM on November 2009 is selected to distinguish the response of GPS PWV changes on the heavy rainfall occurrence.

MATERIALS AND METHODS

Dataset and location: For GPS PWV computation, GPS and the surface meteorological data are required. Department of Survey and Mapping Malaysia (DSMM) supplied the GPS data for this study. The station is located at Kuala Krai, Kelantan (KRAI:) as shown in Fig. 1. The GPS system used a Trimble NetR5 dual-frequency and mounted at 31.77 m above mean sea level. The system was configured to log the GPS data in 15 sec interval.

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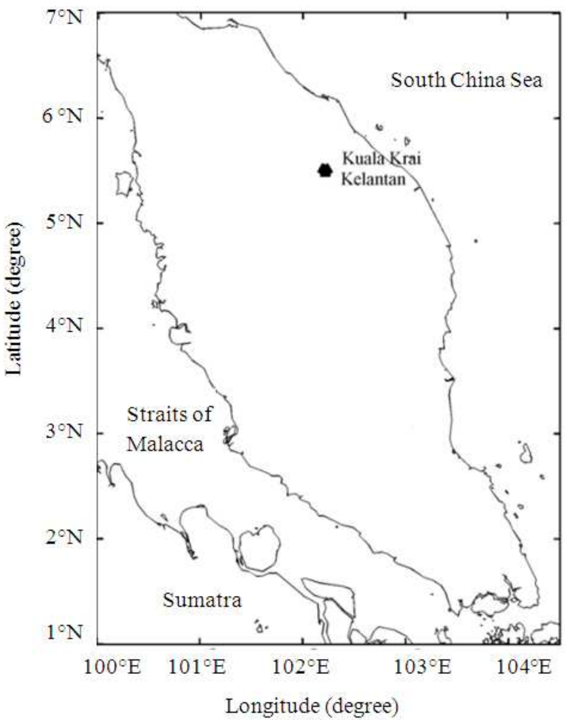

Fig. 1: Location of the Case study at Kuala Krai, Kelantan

The surface meteorological data was bought from the Malaysia Meteorological Department (MMD). The meteorology sensor is located at geographic: "05°30'01"N latitude, 102°12'11" E longitude which is about 2 km away from the GPS station. The dataset consisted of surface pressure (mbar), air temperature (°C) and relative humidity (percent) with a one-minute sampling rate. Both GPS signals and the surface meteorological data were used to determine PWV. Detailed of GPS PWV determination for this study can be found in Suparta *et al*. (2008).

Flood monitoring method: According to the Gong Kedak MMD office report, the heavy rainfall has been started from 18 until 24 November 2009 (GKFO, 2009. However, the flood was continuously occurred between 23 and 27 November. To insight these events that may affect the water vapor distribution; the severe flood is monitored by an indirect way through the observed 'flat' variation of PWV. This monitoring principle was used to detect the lightning occurrence as reported by (Suparta *et al.*, 2011) as shown in Fig. 2.

To establish the GPS PWV changes due to heavy rainfall occurrences, rain data from nearby rain gauge station (05°31'41" N, 102°12'32"E and 3 km away from GPS station) was compared.

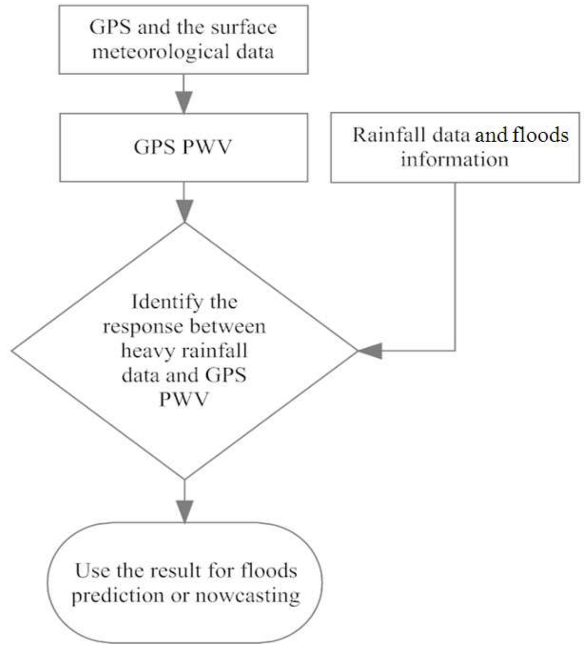

Fig. 2: The processing method and result interpretation

The rain data were supported by the Malaysian Irrigation and Drainage Department (DIDM) with time resolution intervals of 5-min. Then, the total daily rainfall was calculated to strengthen the rainfall pattern in November 2009.

Finally, the GPS and meteorology data were averaged into 3-h intervals. The analysis carried out was then focused on GPS PWV changes that occur prior to the heavy rainfall. The intention of this study is to monitor the PWV changes during the severe flood. Therefore, more analysis for another parameter that associated with PWV is plotted.

RESULTS

Surface meteorology and GPS PWV response on heavy rainfall: Figure 3 shows the response of GPS PWV and the surface meteorological element during the heavy rainfall at Kuala Krai in November 2009. There are two periods of heavy rainfall has been identified in this figure. The first period was occurred from 4-6 November 2009 (as Case 1) while the second period is longer, which was occurred from 18-24 November 2009 (as Case 2). In addition, the total daily rainfall response for November 2009 is presented in Fig. 3d. All the surface meteorological elements as shown in Fig. 3a-3c have been identifying a significant unnatural peak during the heavy rainfall. Although the unnatural peak for surface pressure in Fig. 3a is indistinct, the apparent to its unique variation was detected through the statistical Table analysis presented in Table 1. The other statistical analysis for temperature and humidity were compiled in Table 2 and 3.

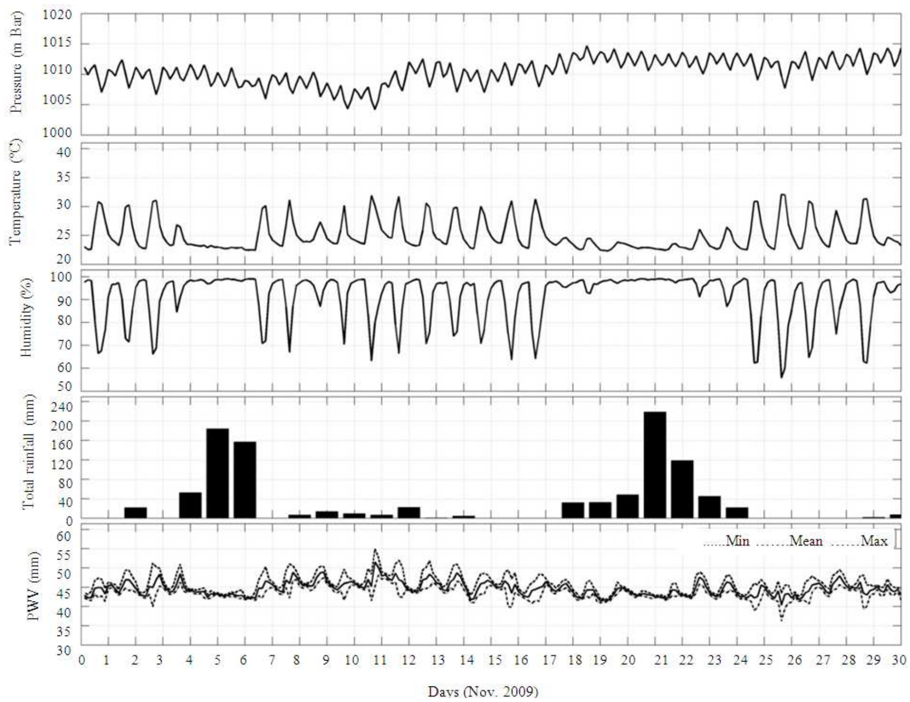

Fig. 3: The response of PWV and meteorological data during heavy rainfall

Table 1: The statistical data for pressure (mbar)

Category	Min	Mean	Max	STD	Δ
Case 1	1007.8	1009.6	1011.6	1.13	3.83
Case 2	1009.9	1012.3	1014.7	1.09	4.79
Case 3	1004.2	1010.0	1014.3	2.16	10.14
1 month	1004.2	1010.5	1014.7	2.13	10.53

Table 2: The statistical data for temperature (°C)

Category	Min	Mean	Max	STD	Δ
Case 1	22.48	23.43	26.83	1.06	4.35
Case 2	22.30	23.4	26.44	0.92	4.14
Case 3	22.46	25.79	32.09	2.77	9.62
1 month	22.30	24.99	32.09	2.58	9.79

Table 3: The statistical data for humidity (percentage)

Category	Min	Mean	Max	STD	Δ
Case 1	84.42	97.24	99.05	3.19	14.63
Case 2	89.92	97.23	99.18	2.41	12.26
Case 3	55.83	88.62	99.25	11.58	43.42
1 month	43.42	91.49	99.25	10.39	43.42

Table 4: The statistical data for GPS PWV (mm)

Category	Min	Mean	Max	STD	Δ
Case 1	42.14	43.77	48.5	1.34	6.36
Case 2	41.43	43.72	47.58	1.39	6.15
Case 3	40.34	45.06	51.56	1.87	11.23
1 month	40.34	44.61	51.56	1.82	11.23

Table 5: Summarize of wind Speed during the first and second heavy rainfall events

	Wind class (%)				
Condition	Calm	Light air	Light breeze	Gentle breeze	Moderate breeze
Case 1	1.4	18.8	19.4	37.5	23.6
Case 2	7.7	34.5	36.3	20.2	1.2
Case 3	14.2	47.9	31.9	5.6	0.4

The minimum pressure for Case 1 and 2 was observed higher of about 0.5% compared to the Case 3. In contrast, the mean value for Case 1 is almost the same with Case 3, while Case 2 was higher of about 0.2% compared to the Case 3. The trend is slightly different for maximum value where for Case 1 is 0.3% lower than the Case 3 while for Case 2 is almost the same with Case 3. The low STD is represented a low variation of pressure data during the heavy rainfall periods. As a result, the pressure variation was observed low for Case 1 and 2 of about 48.6% compared to the Case 3. In addition, the different between maximum and minimum value and range (Δ) can be used to prove the small variation of observed parameters during the heavy rainfall. For pressure data, the Δ for Case 1 and 2 were 3.83 and 4.79 mbar respectively, which is lower than the Case 3 with 10.14 mbar.

From Table 2, the minimum temperatures for all cases are between 22.30 and 22.48°C. However, the mean temperature for Case 1 and 2 is lower than the Case 3 of about 9.2%. The trend is same for maximum value where the Case 1 and 2 is lower of about 17% compared to the Case 3. The STD shows low variation for Case 1 and 2 with values of 1.06 and 0.92°C, respectively. In contrast, the variation in temperature was higher for Case 3 of about 2.77°C. The Δ for Case 1 and 2 was lower than the Case 3 of about 5.38°C. However, the Δ for both cases is still lower than the Case 3.

For humidity, the result is presented in Table 3. From the table, the minimum humidity for Case 1 and 2 is higher about 36% than the Case 3. However, the trend for mean value is lower of about 8.9% compared to the mean value for Case 3. Furthermore, the maximum humidity is 100% for all cases. The variations were observed low during Case 1 and 2 at 3.19 and 2.41% respectively instead of 11.58% in Case 3. This low variation can also be monitored using the Δ.

Figure 3e presents the GPS PWV variation with minimum, maximum and mean values. The figure clearly shows that the GPS PWV variation is lower for Case 1 and 2 while for Case 3 tending to normal. The GPS PWV results for all Cases are presented in Table 4. From the table, the minimum GPS PWV was observed 40.34 mm for Case 3 which is lower than that of Case 1 and 2 with PWV content of 42.14 and 41.43 mm, respectively. However, the trend in the mean value was contrast compared to the Case 3, which is higher of about 2.9% than the Case 1 and Case 2. Similar to the mean, the maximum and STD values for Case 1 and Case 2 are observed lower of about 6.8 and 27% respectively than the Case 3. The Δ value was also observed a similar trend to that of mean and maximum.

Wind activity: Figure 4 shows the wind speed and the direction for Case 1 and 2 in (a) and for Case 3 in (b). It was about 94.2% of the observation period during the Case 1 and 2 is windy. The highest wind speed was recorded at the range 5.5-8.0 sec^{-1}. Overall wind activities during these two cases were summarized as moderate breeze (7.9), gentle breeze (25.4), light breeze (31.3) and light air (29.6%) Beaufort Wind Scale, 2011. Most of the wind source blew from the northeasterly direction as shown in Fig. 4a.

In contrast, the wind direction in Case 3 is almost from the southwesterly direction. Although the highest wind speed range is the same as Case 1 and 2, but their occurrence during the Case 3 is only 0.4%.
Conclusively, the wind during this period was categorized as light breeze (31.9) and light air (47.9). About 14.2% of wind activity during Case 3 is calm condition (Fig. 4b).

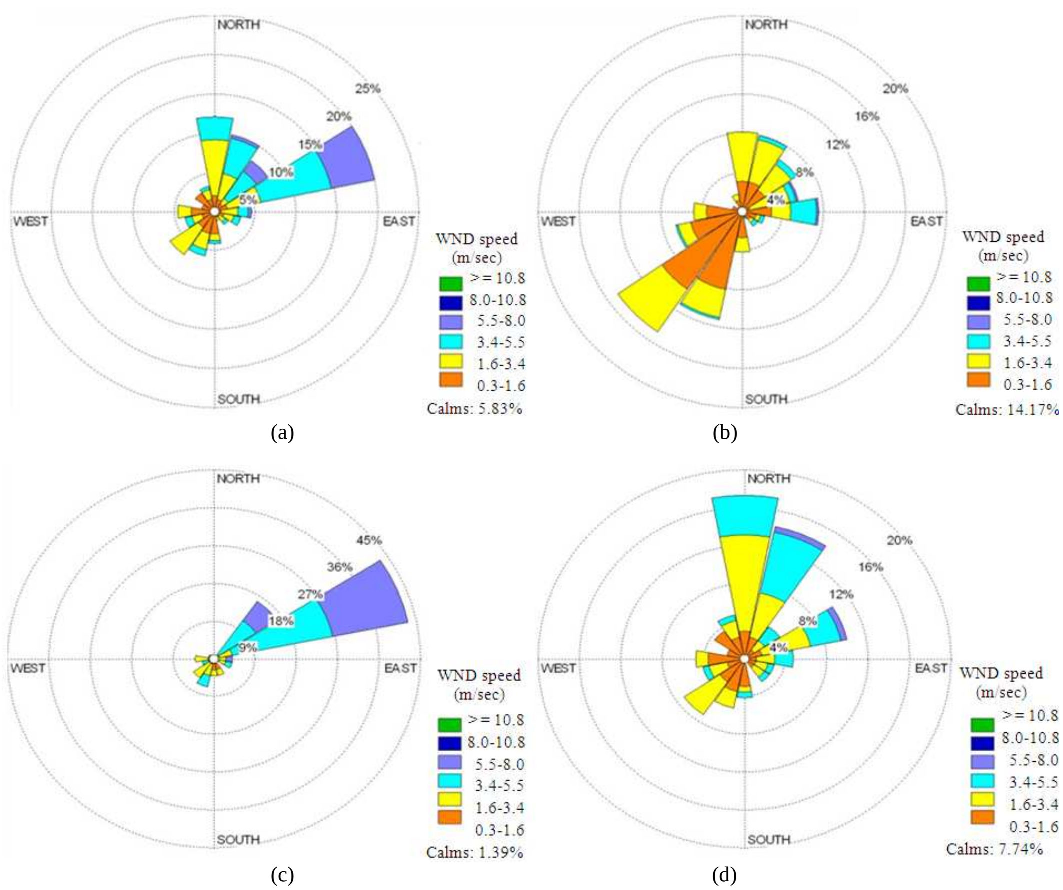

Fig. 4: Wind activity at Kuala Krai in November 2009 (a) During Case 1 and Case 2, (b) During Case 3, (c) During Case 1 and (d) during Case 2

The wind activity for Case 1 and 2 is presented in Fig. 4c and d. For the Case 1, more than 95% of the wind source was blown from the Northeasterly direction (near to east). For Case 2, most of the wind source was blown from the North and Northeast direction. From Table 5, the wind activity during the Case 1 is categorized as a gentle breeze. In contrast during the Case 2, the wind activity was broken into light air and light breeze categories. The calm duration for Case 2 was higher (7.7%) compared to the Case 1 (1.4%).

DISCUSSION

Radar and satellite images: To show the evidence on occurrence of a huge rainfall event at the particular area, both radar and satellite images have been used as shown in Fig. 5. The studied location is marked as a red arrow. Radar images are to show the rainfall activities, while satellite images purposely to show the accumulated cloud cluster at the area on 18, 19, 22 and 25 November 2009. For radar images, the dark blue indicating the lowest rainfall rate while the light blue and light green are as an indicator for the higher rainfall rate. As well, blue and red color in the satellite images representing of low recorded temperature. This low temperature can be associated with the present of large cumulonimbus cloud clusters, which can cause heavy rainfall and thunderstorms over the area.

As shown in Fig. 5a-c, the scattered and widespread of heavy rainfall has been occurred over Kelantan and Terengganu on 18, 19 and 22 November 2009. On the other hand, the distribution of cloud clusters that act as a rain reservoir during the same days was monitored through the Fig. 5e-5g.

From both radar and satellite images, a large of cumulonimbus cloud was formed over the East part of Peninsular Malaysia on 18, 19 and 22 November 2009 which caused the heavy rainfall and thunderstorm at that area. According to the report prepared by Gong Kedak MMD office, the rainfall activity was occurred throughout the day for eight consecutive days which begun on 17 November 2009 (GKFO, 2009). In addition to the clouds, Fig. 5d and 5h show the clear sky over Kelantan and Terengganu on 25 November 2009. From Fig. 5d, only a scattered light rainfall occurred at Kelantan and was supported by satellite image in Fig. 5h where no more cloud cluster can be observed over the area.

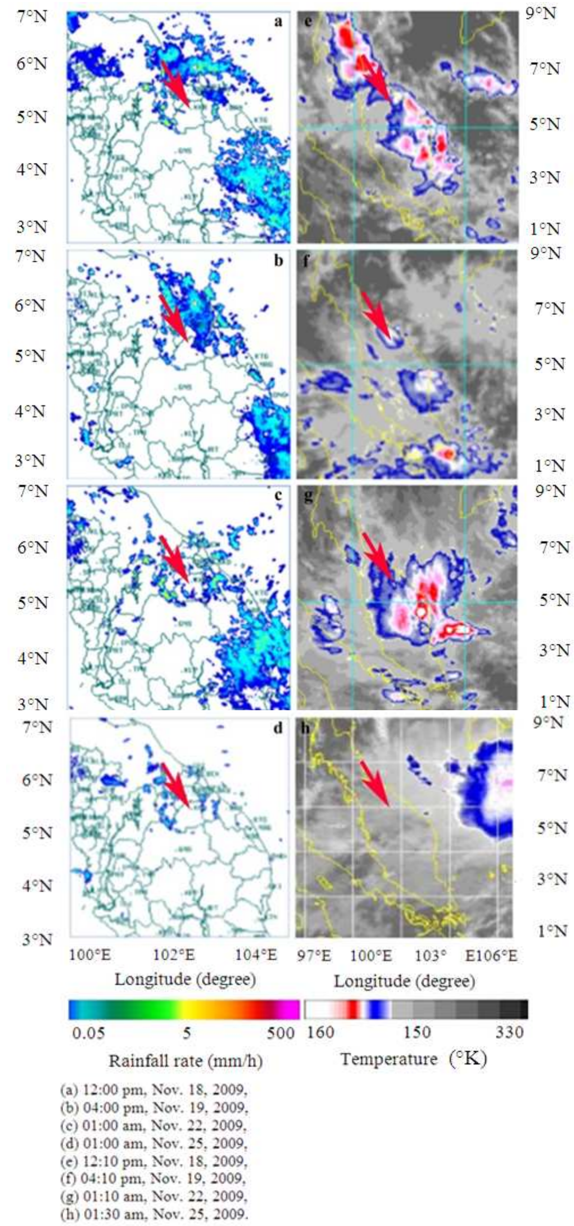

Fig. 5: Selected radar (a-d) and satellite images (e-h) in 18, 19, 22 and 25 November 2009. Figures are adapted from MMD

Response from GPS PWV and surface meteorology: The noticeable fluctuation at PWV and the surface meteorological in Fig. 3 is commonly associated with the exposure level of land surface by sunlight.

As shown in the figure, all meteorology data were clearly flattened during heavy rainfall, especially for Case 1 and 2. The signature of unnatural peak of surface pressure for 3-h average can only be observed using the statistical analysis.

Pressure data varies widely on earth and shows a semi-diurnal cycle caused by global atmospheric tides. This tidal effect is zonally dependent, which strongest in equator and almost zero in polar. Therefore, the influence of local climate activity to contribute in pressure development is small compared to the other meteorology element such as temperature and humidity. On the other hand, the relationship between the surface temperature and PWV is directly proportional but both of them are inversely proportional to the relative humidity.

There are two hypotheses can be made related to the flattened on PWV variation during the heavy rainfall. First, a vast condensation process may take part over the area due to cold surged by strong winter monsoon. The strong winter monsoon is established progressively over the South China Sea (SCS), first appearing over its northern part in September, reaching its central in October and covering the entire SCS in November (Wang *et al*., 2005). Note that the Case 1 and 2 incidents were occurred on November where the monsoon completely influences to local climate activity. Furthermore, the present of cold surge was characterized by a steep rise of surface pressure, a sharp drop of surface temperature and strengthening of northeasterly surface winds and has matched to our result (Chang, 2004).

Second, the thick cloud covered over the area reduces the effect of sun heating to the land surface and causes a low evaporation process. Although the source of water vapor is lower than normal condition, the occurrence of heavy rainfall accompanied by the wind activity will reduce the water content in the atmosphere. This evidence is supported by radar and satellite images, where a huge cloud cluster was blown from the South China Sea.

For Case 1, the rain was occurred in 3 consecutive days with accumulated rainfall of 391 mm. However, the duration of rainfall for Case 2 was longer of about 7 days with total amount 514.8 mm. In addition, the wind speed for Case 1 was recorded stronger than for Case 2 that may shift the 'rain cloud' to the other area. Although the both cases showed a similar response on the GPS PWV, the duration and amount of rainfall as well as the wind activity influence is the respond for unavailability of flood for Case 1.

CONCLUSION

The use of GPS derived PWV to detect and characterize a specific atmospheric event such as severe flood is particular targeted region is an innovator. Based on the GPS and the surface meteorological observations, the influence of severe floods due to heavy rainfall in November 2009 monsoon on PWV has been detected. The GPS PWV was marked flat during these events, which STD reduced of about 26.4 and 23.6% for Case 1 and Case 2, respectively. For Case 3, the result shows a similar trend to the whole month of observation. However, the influence from other meteorological elements such as wind activity and tidal circulation must be taking into account since no incident of flood has been reported during the heavy rainfall for Case 1. Undetected flood for Case 1 by MMD is possibly due to overall wind speed in Case 1 was higher than the Case 2, which is brought out the precipitation elsewhere.

As a conclusion, the case of heavy rainfall can reduce the PWV content in the troposphere. The low of PWV during the severe flood can be highlighted due to the cold air from precipitation condensed the moisture. In another note, cold air cannot hold much the water vapor in the atmosphere and as a result, the water particles become condensed to dry air and light precipitation occurs. To strengthen the association between GPS PWV during the severe flood, a longer historical data and various locations are needed. This would remain for a further research.

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