

# Analysis of PWV Derived from the GNSS CORS Stations for Determining the Onset of the Southwest Monsoon in Thailand

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## Abstract

*This research shows a new threshold for identifying the onset of southwest monsoons using Precipitable Water Vapor (PWV) obtained from GNSS Continuously Operating Reference Stations (CORS) in Thailand by analyzing data from 2007 to 2016. It was found that PWV values for rainy days are higher than non-rainy days. The average PWV for the years 2007-2016 of CHAN station in May was used to determine the new threshold. This new threshold is met when the average value of PWV in May exceeds 58.50 mm for three consecutive days. During the ten years of the study period, the onset date calculated from this method varies by no more than 1-3 days from that calculated by the Thai Meteorological Department (TMD) method, except for 2008 and 2010, when the variance is more than three days. As for other regions namely the central region, the northeast region, and the northern region, it was found that the calculation of the onset of the monsoon season typically varies by 3-5 days.*

## 1. Introduction

Meteorology, which is the study of the atmosphere of the earth by focusing on the weather forecast and the process of the weather, is an important field of science. Meteorological phenomena are observable weather events. These events are caused by fluctuations in factors present in the Earth's atmosphere, such as temperature, air pressure, steam, and other elements. Various weather changes have been found to occur as a result of climate change in the troposphere layer. Therefore, climate tracking is very important because it allows for assessment of climate change that may affect the future. However, study of climate change requires the use of data sets that result from long-term observation that goes on for decades or longer because climate change is a slow process. Even so, current changes are occurring faster than before due to the effects of global warming, which are increasingly intense.

Thailand is located in the Asian monsoon region. The seasonal sea breeze brings water vapor into the continent. Examples of these sea breezes are the monsoon winds in the south and southeast of Asia. Southwest monsoon winds blow into Thailand in May and October. However, the El Niño and La Niña phenomena, including climate change, cause changes in the timing of the seasons, which may be irregularly shorter or longer than usual. This change affects water management plans and agricultural

products, the main products of Thailand. Determining the time of the onset of the monsoon is important because it is crucial for agricultural planning and water management. Farmers can use this data to decide when to plant or harvest crops. Since the start date and period of the monsoon change each year, farmers and governments need reliable methods for predicting these changes annually. That responsible for water management and cultivation tends to use the days and times of the monsoon from previous years as a reference. However, problems arise if the monsoon comes later than usual as water deficits will occur. Also, if the monsoon is longer than usual, there will be too much water. In both cases, damage to crops is the result. Therefore, being able to identify the timing of the beginning of the monsoon is very helpful (Uang-aree et al., 2015).

Precipitable water vapor (PWV) -- PWV is that the quantity of total vertical steam expressed in kilograms per square meter ( $\text{kg/m}^2$ ) or height relative to water in millimetres (mm) -- is a very important factor in atmospheric phenomena. Understanding more about PWV allows us to understand more about the climate of the planet. In particular, the distribution of PWV is very important in understanding geophysics. Therefore, PWV is employed as a variable in climate studies at the worldwide, regional and local levels. (Liang et al.,

2015). Additionally, PWV absorbs heat, causing the temperature of the atmosphere to rise, which is an important variable in tracking the effects on global warming (Greenhouse Effect). In research work, PWV data is used to study the occurrence of storms, water change cycles, and is also used in the Numerical Weather Prediction (NWP) model (Bevis et al., 1992). The PWV derived from the ground-based GPS systems began in 1992 (Bevis et al., 1992) and has been continuously evaluated and improved (Rocken et al., 1993, Bevis et al., 1994, Rocken et al., 1995, Duan et al., 1996, and Tregoning et al., 1998) owing to its importance in the work of weather prediction, weather monitoring, atmospheric analysis, and numerous other applications. The application of PWV values in meteoric work (GPS-Meteorology) continues to be an important item of attention and ongoing analysis. However, using data from ground-based GPS stations to determine the amount of water vapor in the atmosphere in the form of precipitable water vapor (PWV) (Bevis et al., 1994) is still an effective method. Also, this provides an inexpensive methodology that can be used to continuously monitor weather conditions (Coster et al., 1996, Jade and Vijayan, 2008 and Suparta and Iskandar, 2012).

In addition, the PWV derived from ground-based GNSS stations (GPS-PWV) has an accuracy similar to that of more expensive meteorological instruments (Li et al., 2015) such as Radiosonde (RS), Microwave Radiometer (MWR), and data from meteorological satellites, etc. To prove the initial assumptions for using GPS-PWV values for meteorological applications in Thailand, this paper begins by considering previous studies on possible and easy ways to use PWV obtained from GPS. In Thailand, it has been confirmed that PWV values can be obtained correctly from GNSS observations (Satirapod et al., 2010, Satirapod and Rizos, 2011, Suwantong et al., 2017, Charoenphon and Satirapod, 2019 and Meunram and Satirapod, 2019). As for the research related to the use of PWV to identify the entry into the monsoon season in Thailand, there have been trials on the possible methods of using PWV obtained from GPS, such as using GPS-PWV to predict Southwest monsoons during the rainy season (Takiguchi et al., 2000) and experimenting with GPS-PWV to study new methods for identifying the onset and withdrawal of southwest monsoon in Northeastern Thailand (Uang-aree et al., 2015). These research studies, however, used PWV data for a short period only, and were limited by the fact that ground-based GNSS stations do not cover all areas in Thailand. Therefore, in this research, the 11 widely-distributed CORS in Thailand that are

distributed throughout the country, and PWV data gathered between 2007 and 2016, are used to analyze the onset of the monsoon season in Thailand. The researcher has published a previous article which relied on PWV time-series to find Trend and Seasonal values in order to find the relationship between PWV and Rainfall. It was found that the rainy season (around the middle of May to the end of October) shows the smallest fluctuation of the PWV and the high average PWV, which is consistent with the 24-hour cumulative rainfall data (Trakolkul and Satirapod, 2019).

## 2. Methodology and Observation Model

### 2.1 Data

In this research, the PWV data obtained from the GNSS CORS station in Thailand from the Department of Public Works and Town & Country Planning (DPT) were collected from 2007-2016 by Precise Point Positioning (PPP) GNSS technique. Rainfall data in this research was obtained from the Thai Meteorological Department (TMD). The relationship between the PWV data obtained from the estimated GNSS data and the rainfall information from the rainfall monitoring station near the GNSS CORS station was then analyzed. (as shown in Figure 1)

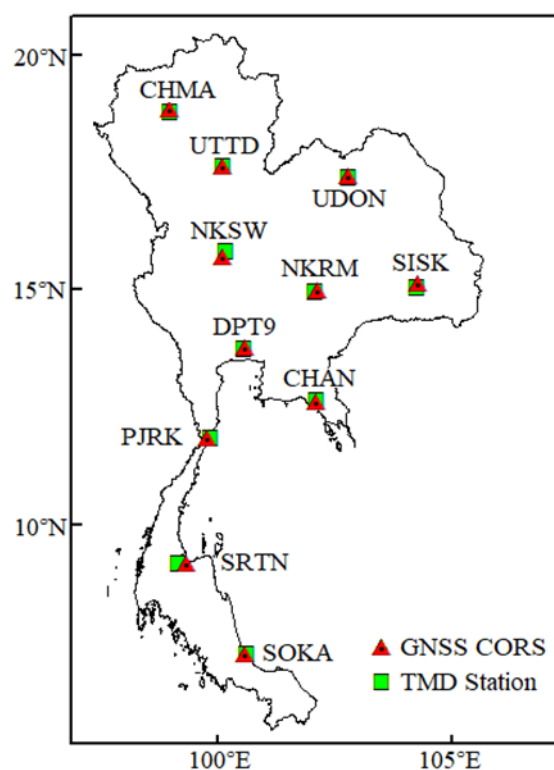


Figure 1: Location of the meteorological stations and GNSS CORS stations for this study

## 2.2 Precise Point Positioning (PPP)

The PPP technique is a methodology of determining positions that can provide accuracy to the centimeter-level. The mathematical model of the positioning algorithm is also determined using ionosphere-free combination for the pseudorange and carrier phase GNSS observations to eliminate the first order of Ionosphere effects. The simplified observation equation for PPP techniques (Kouba and Héroux, 2001) can be shown as follows:

$$P_{L3} = \rho + c(dt - dT) + (M \times ZTD) + \varepsilon_p \quad \text{Equation 1}$$

$$\phi_{L3} = \rho + c(dt - dT) + (M \times ZTD) + N\lambda + \varepsilon_\phi \quad \text{Equation 2}$$

According to Meunram and Satirapod, (2019) “where  $P_{L3}$  and  $\phi_{L3}$  are the ionosphere-free combination of pseudorange and carrier phase observations,  $\rho$  is the geometrical variation between satellite and receiver coordinates,  $c$  is the vacuum speed of light,  $dt$  and  $dT$  are a clock error of receiver and satellite, respectively,  $M$  is mapping function, which is a function of satellite elevation angle (degrees),  $ZTD$  is tropospheric delay in zenith direction,  $N$  is the ambiguity number of ionosphere-free combination in carrier phase,  $\lambda$  is wave length of the carrier-phase ionosphere-free, and  $\varepsilon_p$  and  $\varepsilon_\phi$  are the multipath error and observation noise of ionosphere-free combination observation”.

## 2.2 Tropospheric Delay

In the atmosphere, the troposphere is the lowest layer, about 8 - 15 kilometres away from the Earth's surface. It consists of both dry and wet elements. About 90% of the tropospheric delay is caused by the ultimate hydrostatic delay (ZHD). The amount of wet delays (ZWD) accounts for the remaining ~10% (Davis et al., 1985). ZWD can be expressed in the form of ZTD and ZHD as the equation below:

$$ZWD = ZTD - ZHD \quad \text{Equation 3}$$

As for ZHD, it will vary with temperature and air pressure. For the discrepancy in this section, the Saastamonien model (Saastamoinen, 1972) can be used to write the following equations:

$$ZHD = \frac{2.2768 \times P_s}{1 - 0.00266 \cos(2\phi) - 0.00000028H} \quad \text{Equation 4}$$

where  $P_s$  is the surface air pressure (hPa),  $\phi$  is the latitude at the station (rad), and  $H$  is the height above the mean sea level (m). PWV is the total amount of vertical steam above the receiver, and can be calculated from ZWD through the following formula (Bevis et al., 1992):

$$PWV = \Pi * ZWD \quad \text{Equation 5}$$

In equation (5),  $\Pi$  is a function of weighted mean temperature ( $T_m$ ). The detailed equation for calculating  $\Pi$  is shown as follows (Bevis et al., 1992):

$$\Pi = \frac{10^6}{\rho_w R_v \left( \frac{k_3}{T_m} + k^2 \right)} \quad \text{Equation 6}$$

where  $\rho_w$  is the density of liquid water (999.97 kg/m<sup>3</sup>),  $R_v$  is the specific gas constant of water vapor (461.525 JK<sup>-1</sup>kg<sup>-1</sup>),  $k^2$  is 22.1 K/hPa,  $k_3$  is 3,739 K<sup>2</sup>/hPa,  $T_s$  (°C) is the surface temperature and  $T_m$  is the weighted mean temperature of the atmosphere where  $T_m = 113.2914 + 0.6066T_s$  (Suwantong et al., 2017). The GNSS PWV data processing steps can be described in Figure 2.

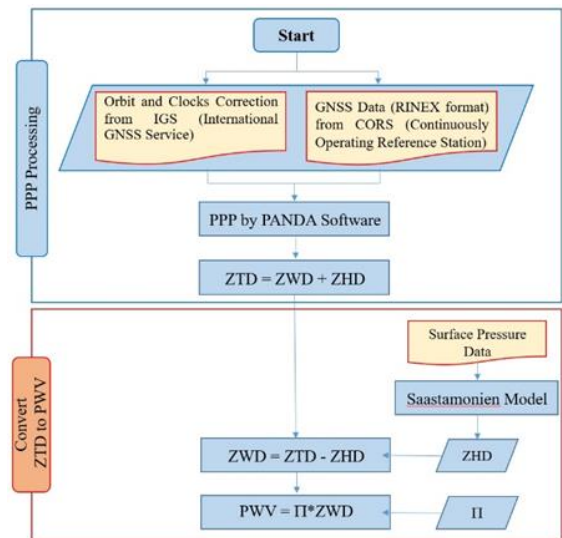


Figure 2: Data Processing from Tropospheric Delay to PWV values

## 3. Processing and Analysis Step

### 3.1 PPP Processing

In this article, PWV data is processed using PPP techniques by the PANDA (Positioning and Navigation Analysts) software package developed at Wuhan University (Li et al., 2015). This PPP processing allows some settings to be included in

precise solutions, such as satellite orbit errors and offset satellite clocks from IGS (Kouba, 2015). GNSS data of the Department of Public Works and Town & Country Planning at 11 stations including Chiang Mai (CHMA), Uttaradit (UTTD), Udon Thani (UDON), Sisaket (SISK), Nakhon Ratchasima (NKRMM), Nakhon Sawan (NKSWS), Bangkok (DPT9), Chanthaburi (CHAN), Prachuap Khiri Khan (PJKK), Surat Thani (SRTN) and Songkhla (SOKA) are stored in RINEX format. The data is then processed using PANDA and Global Mapping functions (GMF) to find the Zenith Total Delay (ZTD).

### 3.2 Conversion of ZTD to PWV

The ZTD derived from the PPP technique can be represented in two components: ZHD and ZWD. ZHD can provide better accuracy using data from surface meteorological measurements. However, ZWD has a high variance, often used as an approximation parameter. To achieve higher accuracy, it can be converted to PWV using the mean temperature data ( $T_m$ ). ZWD can be shown in terms of ZTD and ZHD.

### 3.3 Analyzing the Correlation between PWV and Rainfall

The relationship between PWV and rainfall has been studied. It has been found that the average PWV is higher for rainy days than non-rainy days (Manandhar et al., 2016). In this research, the relationship was determined by plotting the relationship between the PWV and Rainfall of CHAN station in 2011 and 2012, which were the years without the El Niño and La Niña phenomena, for preliminary consideration in determining the onset of the southwest monsoon in Thailand.

## 4. Results and Discussions

### 4.1 PWV and Rainfall

For rainfall and PWV, rainfall data from the rainfall monitoring stations near the GNSS CORS stations were recorded by TMD in order to analyze the correlation with PWV data obtained from the estimated GNSS data results (shown in Figure 1).

In this case, the data from the rainfall monitoring station located nearest each of the GNSS CORS stations was used. For analysis of the PWV derived from GNSS and rainfall data, the CHAN station was chosen for this analysis because the distance is only 1 km. The PWV and Rainfall data at CHAN station between 2011 and 2012 was plotted to determine the relationship as follows. When analyzing the amount of PWV for rainy and non-rainy days, PWV shows some changes, as shown in Figure 3. The average

PWV per day per month of 2011 is shown for both rainy days (blue bars) and non-rainy days (orange bars) and shows that the average PWV for rainy days is higher than non-rainy days. From this analysis of 2011 and 2012, we can see the highest differences in the PWV on rainy and non-rainy days gets up to 33.48 mm in January and 36.4 mm in December respectively. As for May, which is the beginning of the southwest monsoon season, there is a difference of PWV between the highs and lows of rainy days and non-rainy days of only 2.51 mm and 2.09 mm respectively. Based on the monthly average PWV distribution data for rainy and non-rainy days, it was found that the distribution patterns were consistent with the southwest monsoon. Therefore it is possible to use PWV data to determine the onset of the monsoon season.

### 4.2 Threshold PWV

Some relationships between PWV and rainfall have already been identified in previous sections. An increase in PWV means rain, but the PWV must first be determined. The PWV of the criteria must be set in such a way that, when the PWV in a certain time exceeds the specified value, this criterion will clearly identify that the rainy season is about to begin. The month of May for the years 2007-2016 was chosen for testing. Table 1 shows the average PWV values in May for the ten-year period of 2007-2016, which will be used as the baseline for determining if the PWV value exceeds the threshold. The threshold value of 58.50 mm was chosen from the average PWV values on rainy days for May of the years 2007-2016. Figure 4 shows the Cumulative Distribution Function (CDF) plot for May 2007-2016. For non-rainy days, the PWV is higher than the threshold 20% of the time, and for the rainy day, the PWV is higher than the threshold 50% of the time. The results obtained from using this threshold are discussed in the next session.

### 4.3 PWV and Rainfall with Threshold PWV

The threshold GPS-PWV was tested by checking comparing it with the PWV Time-series of CHAN station and found that the PWV threshold is 58.50 mm or more for more than three consecutive days can be used to identify the onset of the southwest monsoon in Thailand. When comparing with data from TMD (Thai Meteorological Department, 2018), the results are as in the Table 2 below. This new threshold would have been effective in determining the onset of the Southwest monsoon in the period 2007-2016. When compared to the results of the TMD method, the new threshold using GPS-PWV provides a good outcome.

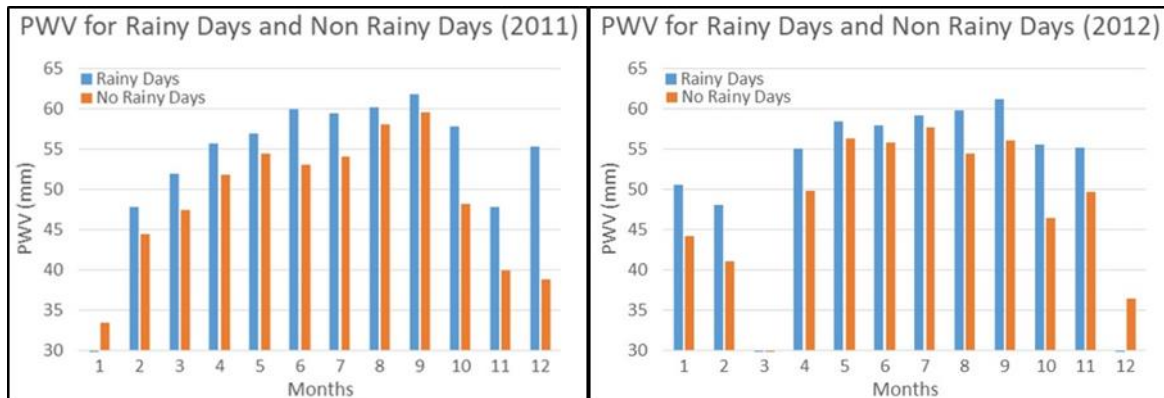


Figure 3: Average PWV per day per month for Rainy and Non-rainy days (2011-2012)

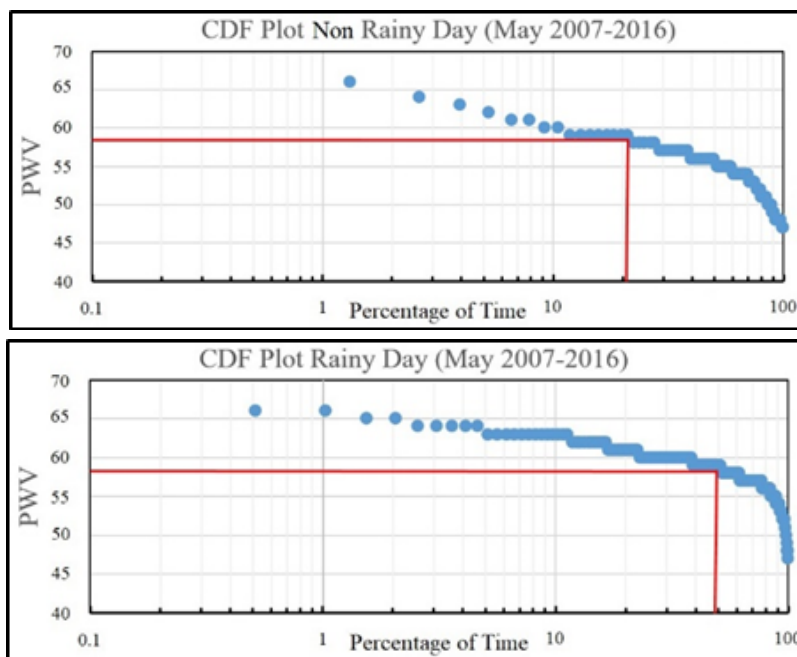


Figure 4: Average PWV per day per month for Rainy and Non-rainy days (2007-2016)

Table 1: Average PWV per month at CHAN station

Year	Rainy Days	Non-Rainy Days
May 2007	59.18	52.67
May 2008	56.73	53.00
May 2009	58.08	51.67
May 2010	59.81	56.57
May 2011	56.95	54.44
May 2012	58.42	56.33
May 2013	58.00	54.09
May 2014	57.71	55.00
May 2015	No Data	No Data
May 2016	61.60	56.75
<b>Average</b>	<b>58.50</b>	<b>54.50</b>

Table 2: Comparison New Threshold PWV of Southwest monsoon onset dates with TMD

Year	TMD	New Threshold
2007	5 May	3 May
2008	10 May	5 May
2009	9 May	13 May
2010	21 May	16 May
2011	6 May	9 May
2012	5 May	6 May
2013	18 May	19 May
2014	27 May	27 May
2015	22 May	No Data
2016	18 May	16 May

The predicted onset of the monsoon season from GPS-PWV methods is within 1-3 days of the TMD method, except for 2008 and 2010, which were both different by more than 3 days. The discrepancies in 2008 and 2010 occurred because those were years that La Niña was in a state that caused heavy rain and a lot of water, which is in line with the results of the new threshold that indicates that the season start date will come earlier than usual more consistently than does the TMD method, which may have errors due to rain before the monsoon and short rain disruption in Season. For this reason the calculated starting and withdrawing dates of the monsoon using the TMD method can be in error. Since the TMD method would consider only the rainy day. If it rains before the monsoon and the rain stops in the season, the consideration of entering the monsoon season will be inaccurate. The comparison of the two methods proves that the GPS-PWV method is more accurate and that it will set the date closer to the observation than the TMD method, with very few exceptions. This method is easy to use as it only requires PWV and does not require information about the amount of rain and wind direction. Using this new threshold, it was found that, after the onset of the monsoon, there will be continuous rainfall. Knowing this information makes it simple to forecast of the day of onset of the monsoon by checking the amount of rain alone. In other words, the PWV can be used to accurately identify the start of monsoon season.

## 5. Conclusion

This study provides an overview of the use of PWV derived from GNSS CORS stations in Thailand, focusing on determining the onset of the southwest monsoon in Thailand. In this paper, PWV obtained from GNSS and meteorological data were studied to assess the relationship used to determine the threshold for identifying the onset of the monsoon

season. The new threshold for GPS-PWV has been established based on the relationship between PWV and Rainfall, including consideration of the average PWV in May for the ten year period of 2007-2016. The threshold for the onset is the day when the average GPS-PWV has been above 58.50 mm for three consecutive days. The threshold results were compared to the TMD method. The comparison shows that the two methods predict dates within 1-2 days of one another, except for the years 2008 and 2010, when predicted dates varied by more than three days. As for other regions in the higher latitudes, namely the central region, the northeast region, and the northern region, when using these new thresholds to determine the onset of the monsoon season, it was found that the onset of the monsoon season in this part will be slower, typically within 3-5 days. The reason is that, in that area, there is a lower average PWV in the CHAN station used in the test, and the CHAN station is located in the eastern part, near the sea and the coast, and is influenced by the southwest monsoon before other regions. This study will be useful in agricultural planning and water management. Farmers can use this information to decide when to plant or harvest crops since they will know with greater accuracy the beginning and the period of monsoon each year.

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