

# Investigating the Relationship between Precipitable Water Vapor and Rainfall Data during Flood Events: A GNSS-Based Study in Thailand

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## Abstract

*This research investigates the correlation between Precipitable Water Vapor (PWV), derived from Global Navigation Satellite System (GNSS) measurements, and rainfall during flood events in Chanthaburi, Surat Thani, and Songkhla, Thailand. Utilizing GPS-PWV and meteorological data collected from 2007 to 2016, the study reveals a significant increase in average PWV during flood events at CHAN, SRTN, and SOKA stations, suggesting its potential as an anticipatory indicator for impending rainfall. The robust correlation between PWV and rainfall patterns underscores the pivotal role of meteorological parameters in shaping PWV distribution. Categorized by flood events, consistent correlations were observed, with Case 1 (2009) showing correlation coefficients of 0.78 for CHAN, Case 2 (2010) displaying correlation coefficients of 0.70 for SRTN and 0.27 for SOKA, and Case 3 (2011) exhibiting correlation coefficients of 0.64 for SRTN and 0.71 for SOKA. These findings contribute valuable insights for precipitation forecasting and flood management, emphasizing the utility of PWV as a reliable tool. Future studies incorporating an expanded network of GNSS CORS stations aim to refine PWV distribution understanding for enhanced monitoring and prediction of precipitation events in the region.*

**Keywords:** Global Navigation Satellite System (GNSS), Precipitation Water Vapor (PWV), Rainfall Data, Flood Events, GPS Measurements

## 1. Introduction

Studying precipitable water vapor (PWV) in the atmosphere is crucial for monitoring climate change, the Earth's greenhouse effect, and predicting precipitation [1]. While various methods exist for determining atmospheric water vapor, such as meteorological satellites and radiosondes, they often suffer from poor temporal resolution and cost constraints [2][3] and [4]. Microwave radiometers face practical limitations in Thailand due to sparse station availability and measurement inconsistencies [5]. In contrast, GNSS-Meteorology, utilizing ground-based GNSS receivers, has emerged as a promising technique due to its affordability, all-weather operability, high accuracy, extensive coverage, and continuous data accessibility [6]. Contemporary researchers are increasingly interested in conducting experiments to forecast extreme events

based on variations in precipitable water vapor (PWV). Most extreme events, such as floods, heavy snowfall, cyclones, and droughts, can typically be identified through surface meteorological parameters, precipitation levels, shifts in wind direction, and other data. GPS-PWV observations for predicting extreme events have been ongoing since the early 20th century. Studies conducted in mid-latitude regions have shown an increase in PWV concurrent with a decrease in temperature during heavy precipitation [7]. Additionally, research indicates a direct correlation between GPS-PWV and precipitation in South China [8]. However, investigations by [9] and [10] have demonstrated a high correlation between PWV and rainfall using GPS data over Peninsular Malaysia.

Nevertheless, these studies have noted discrepancies in results concerning PWV and rainfall trends, primarily due to variations in data resolution and study location.

This study investigates the correlation between GNSS-derived PWV and heavy rainfall intensity to enhance understanding of local weather patterns, improve forecasting accuracy, and develop effective disaster management and water resource planning strategies. Initially introduced by [11], ground-based GPS stations are crucial in regional and local climate research [12]. Ongoing PWV research in Thailand, including time-series analysis [13], contributes to understanding monsoon onset and the impacts of El Niño–Southern Oscillation (ENSO) [14][15][16] [17]. The study by [18] found that areas with differing characteristics may experience varying flood probabilities under similar rainfall conditions. This underscores the importance of precise hydrological data for practical flood risk assessment and management. By leveraging GNSS measurements, particularly GPS-PWV data from Continuously Operating Reference Stations (CORS) managed by the Department of Public Works and

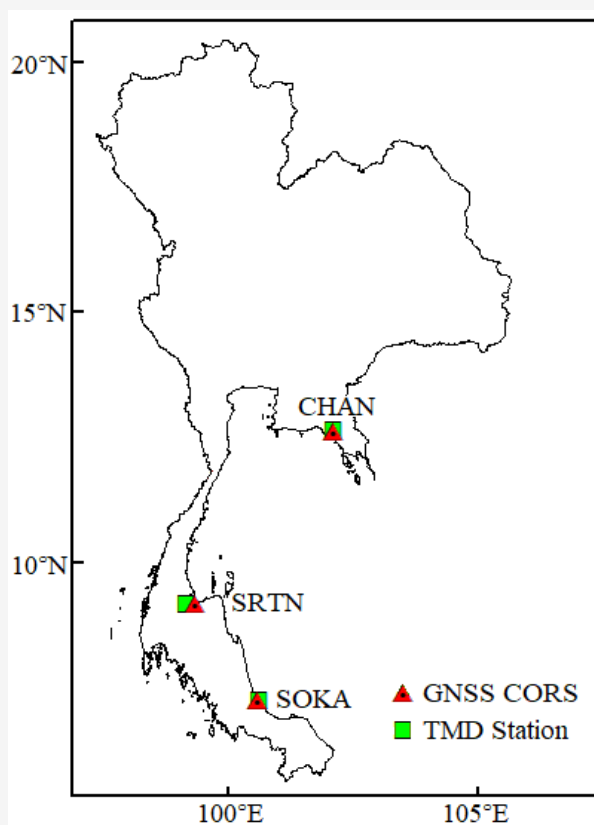
Town & Country Planning, the study aims to establish PWV as a reliable indicator for anticipating rainfall and enhancing Thailand's resilience to flooding.

## 2. Methodology

### 2.1 Dataset and Location

**PWV Data:** Precipitable Water Vapor (PWV) data were collected using Global Navigation Satellite System (GNSS) measurements, specifically from GNSS Continuously Operating Reference Stations (CORS) in the study areas. These stations include CHAN, SRTN, and SOKA, strategically located in Chanthaburi, Surat Thani, and Songkhla, respectively. The GNSS CORS stations provide precise and continuous PWV measurements based on the signals received from global navigation satellites.

**Rainfall Data:** Rainfall data for the relevant periods were obtained from the Thai Meteorological Department (TMD) meteorological stations near GNSS CORS stations. This data served as reference data for analyzing the correlation between PWV and rainfall during flood events.



**Figure 1:** Geographic locations of the meteorological stations and GNSS CORS stations utilized in this study. The figure was adapted from [15]

## 2.2 Time Period Selection

The study will focus on specific flood events identified in Chanthaburi (CHAN), Surat Thani (SRTN), and Songkhla (SOKA). The selected time periods are Case 1 (2009) for CHAN between July 19<sup>th</sup> and July 25<sup>th</sup>, Case 2 (2010) for SRTN and SOKA between October 26<sup>th</sup> and November 13<sup>rd</sup>, and Case 3 (2011) for SRTN and SOKA between March 21<sup>st</sup> and March 30<sup>th</sup>. Additionally, one week before and after each flood event was considered for a comprehensive analysis.

## 2.3 PWV Calculation

In our study, Precipitable Water Vapor (PWV) calculation relies on Zenith Total Delay (ZTD) values obtained from GNSS measurements. We establish the relationship between ZTD and PWV using the Saastamoinen model [19], which considers atmospheric pressure, temperature, and water vapor content. Additionally, the Zenith Wet Delay (ZWD) is a crucial component in enhancing the accuracy of our calculations. Derived from the Precise Point Positioning (PPP) technique, the calculation of ZWD involves subtracting the Zenith Hydrostatic Delay (ZHD) from the ZTD. This parameter plays a pivotal role in our methodology, contributing significantly to the precision of our PWV calculations. Equation 1 represents the calculation of ZWD:

$$ZWD = ZTD - ZHD \quad \text{Equation 1}$$

The Zenith Hydrostatic Delay (ZHD) is a crucial component in our calculations. Its accuracy is improved by incorporating surface meteorological data, especially the mean temperature ( $T_m$ ). By subtracting ZHD from ZTD, we obtain the Zenith Wet Delay (ZWD). This ZWD is then transformed into PWV using a function determined by the atmosphere's weighted mean temperature ( $T_m$ ). This transformation allows us to provide a comprehensive measure of the vertical steam content above a receiver. Equations 2 show the calculations for ZHD and PWV.

$$ZHD = \frac{2.2768Ps}{1 - (2.66 \times 10^{-3}) \cos(2\phi) - (2.8 \times 10^{-7})H} \quad \text{Equation 2}$$

Where  $Ps$  represents the surface air pressure (hPa),  $\phi$  denotes the station latitude (rad), and  $H$  indicates the mean height above sea level (m). After determining the ZWD value from the relationship between ZTD and ZHD, PWV can be calculated using Equation 3.

$$PWV = \Pi \times ZWD \quad \text{Equation 3}$$

$$\Pi = 10^6 \left( \rho_w R_v \left( \frac{k_3}{T_m} + k'2 \right) \right)^{-1} \quad \text{Equation 4}$$

The factor  $\Pi$  determined from Equation 4 depends on the weighted average temperature ( $T_m$ ), where  $\rho_w$  is the density of liquid water,  $R_v$  is the specific gas constant of water vapor ( $461.525 \text{ JK}^{-1}\text{kg}^{-1}$ ),  $k'2$  is  $22.1 \text{ K/hPa}$ , and  $k_3$  is  $3,739 \text{ K}^2/\text{hPa}$ . The  $T_m$  value is derived using an equation from [20]. In terms of data collection and processing, this study utilized rainfall data from the Thai Meteorological Department alongside Precipitable Water Vapor (PWV) data obtained from GNSS CORS stations across Thailand, as depicted in Figure 1. The analysis employed the Precise Point Positioning (PPP) technique. The Zenith Total Delay (ZTD) calculation utilized the Global Mapping function (GMF). According to [15], there is an explanation of the Precise Point Positioning technique (PPP) and Global Mapping Functions (GMF) used to determine the Zenith Total Delay (ZTD).

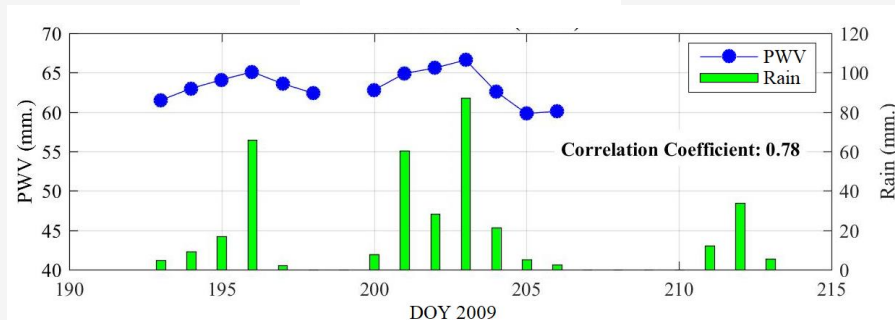
## 3. Results

### 3.1 Comparison of PWV during Flood Events

Correlation coefficients (R) were computed to quantify the relationship between PWV and rainfall during the identified flood events. The correlation analysis was performed separately for each case, examining the stations (CHAN, SRTN, SOKA) to determine the strength and direction of the association between PWV and rainfall. By employing these methodologies, the study aims to provide a comprehensive understanding of the correlation between PWV and rainfall during flood events in the specified regions of Thailand, contributing valuable insights to flood prediction and management strategies. Table 1 illustrates the average Precipitable Water Vapor (PWV) levels one week before and after flood events at the SOKA and SRTN stations, revealing a substantial increase compared to the corresponding period in the previous year. This emphasizes the potential of PWV as a predictor of upcoming rainfall. Furthermore, the correlation between PWV variability during flood events and rainfall patterns emphasizes the influence of meteorological factors on PWV distribution. Notably, the consistent upward trend observed at the CHAN station highlights its significance, warranting further investigation to enhance understanding of PWV trends and facilitate improved detection of forthcoming rainfall events.

**Table 1:** Average PWV for one week before and after the flooding event

Case	Station	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
1	CHAN	59.30	58.31	<b>63.24</b>	62.86	62.56	60.50	62.08	62.36	60.23	-
2	SRTN	-	57.41	53.26	<b>60.24</b>	52.43	52.42	53.98	-	-	-
	SOKA	-	-	56.84	<b>58.92</b>	56.30	54.33	55.39	-	-	-
3	SRTN	50.04	48.08	53.17	45.09	<b>58.61</b>	-	40.76	43.59	42.37	36.90
	SOKA	-	49.21	55.24	49.50	<b>56.76</b>	-	38.54	45.94	37.43	35.50

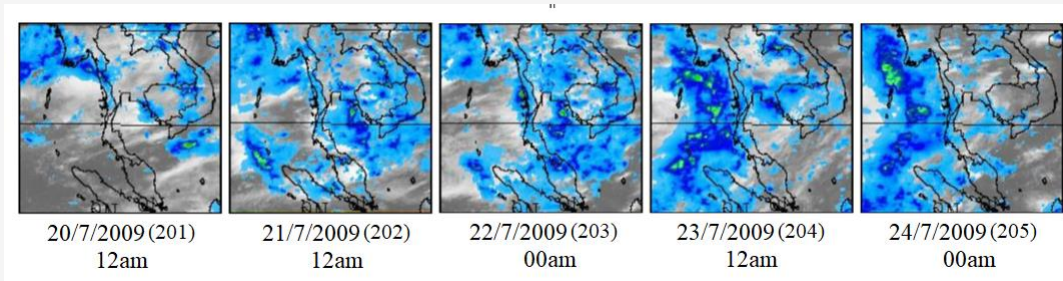
**Figure 2:** Correlation PWV-Rain at CHAN (Case1)

In our study, Case 1 focuses on flood incidents in Chanthaburi province in 2009, explicitly examining PWV dynamics at the CHAN station. We observed a significant elevation in PWV levels leading up to the flooding event, suggesting increased atmospheric moisture content and potentially indicating an impending heavy rainfall episode. The alignment between PWV elevation and the subsequent flood event underscores the predictive value of PWV as a precursor to intense rainfall and flooding. Transitioning to Case 2 and Case 3, which involves flood events in Surat Thani and Songkhla provinces in 2010 and 2011, our analysis encompasses multiple stations in these regions. We identified a consistent pattern of heightened PWV levels preceding the flood events at stations in both provinces, reinforcing the robustness of our findings and underscoring the applicability of PWV as a predictive indicator for flood events in diverse geographical contexts. Additionally, the consistent correlation between PWV variability and rainfall patterns across both cases further underscores the meteorological influence on PWV distribution during flood events in these regions. Overall, our comprehensive analysis across multiple cases elucidates the consistent relationship between PWV levels and flood occurrences, providing valuable insights for enhancing flood prediction and disaster management strategies in Thailand.

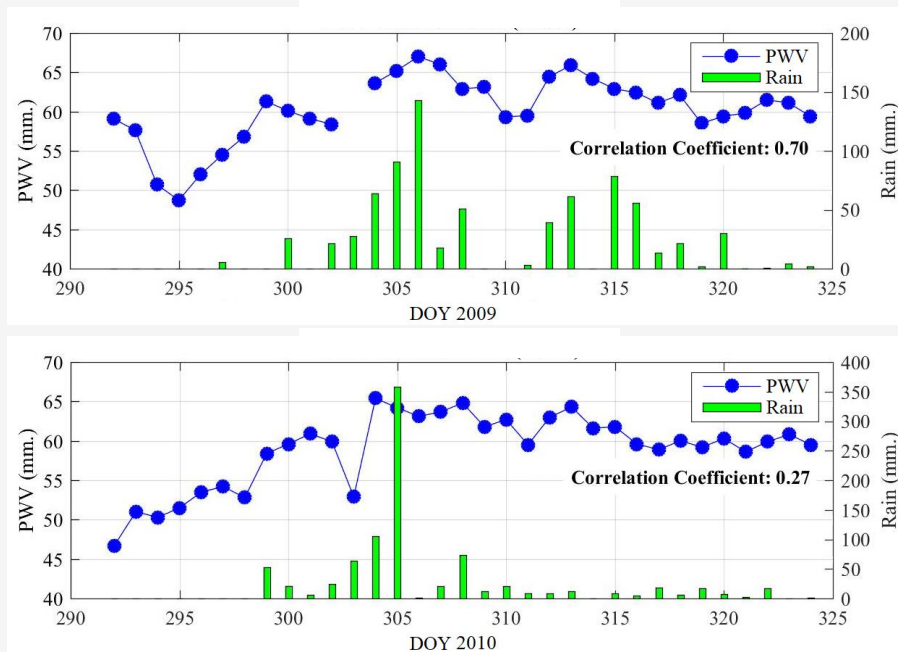
### 3.2 Correlation Analysis

From Figure 2, for Case 1, focusing on the CHAN station in 2009, a strong positive correlation was observed between Precipitable Water Vapor (PWV) and rainfall. The correlation coefficient ( $R$ ) was calculated to be 0.78, indicating a significant and direct relationship between PWV and rainfall during flood events in Chanthaburi Province. This robust correlation suggests that higher PWV values correspond to increased rainfall amounts during the specified period. Therefore, the analysis underscores the utility of PWV as a reliable indicator for anticipating rainfall occurrences, particularly during flood events in the Chanthaburi region in 2009. The cumulative rainfall map from the Naval Research Laboratory of the United States reveals a distinct cluster of rainfall over Trat and Rayong provinces. This cluster persists from July 20<sup>th</sup> to July 23<sup>rd</sup> and gradually diminishes on July 24<sup>th</sup>. This pattern indicates a localized and continuous precipitation event in the specified regions during the mentioned period (see Figure 3).

In Case 2, the weak correlation coefficient of 0.27 observed at the SOKA station in Songkhla indicates that localized meteorological conditions, such as topography, microclimate variations, and local weather patterns, may influence the PWV-rainfall relationship differently than other stations. Additionally, the La Niña event of 2010-2011, as studied by [16], may have contributed to these discrepancies, as La Niña can lead to significant rainfall without substantial anomalies, causing severe weather and floods in multiple areas.



**Figure 3:** Accumulated rainfall CHAN [21]

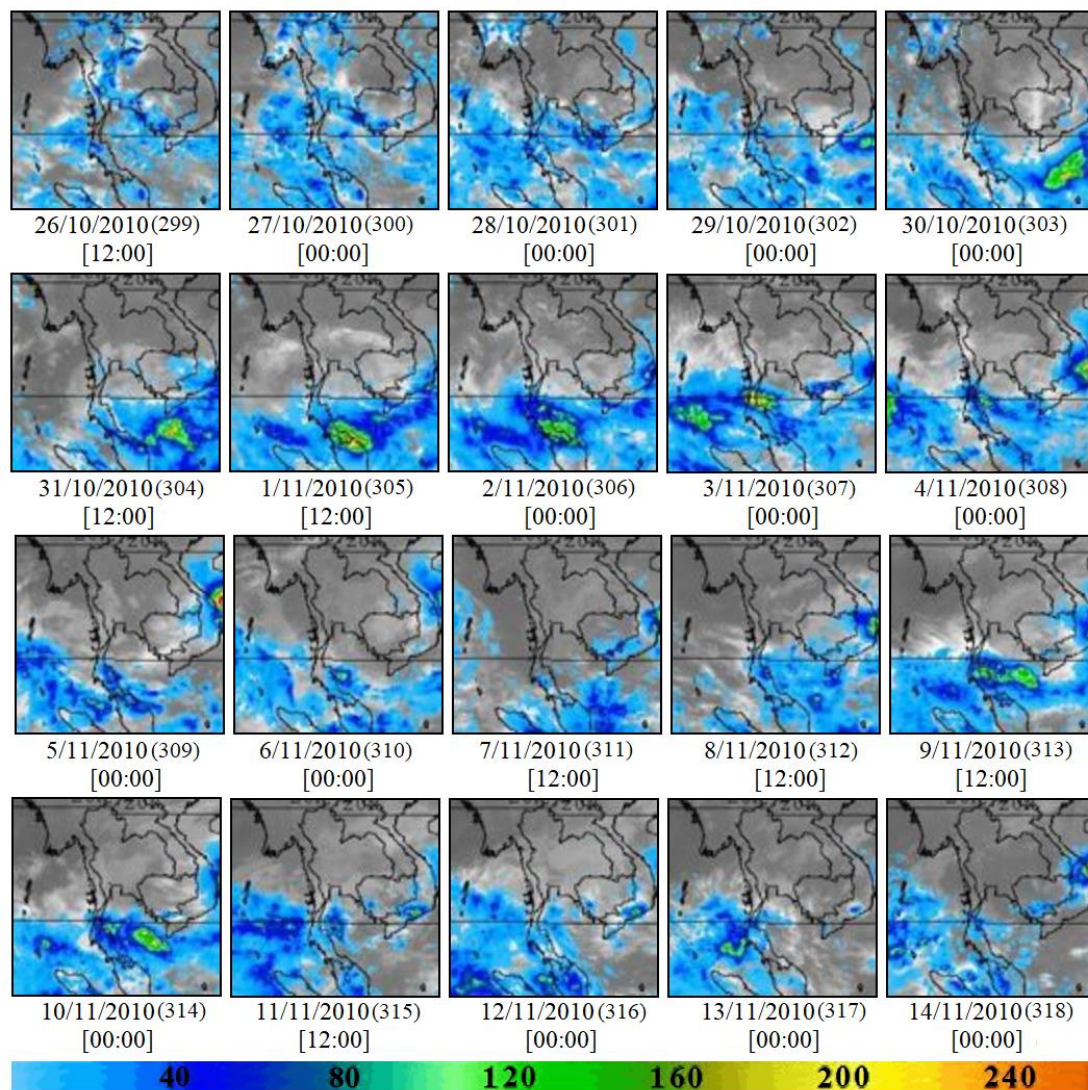


**Figure 4:** Correlation PWV-Rain at SRTN-SOKA (Case2)

Strategies to improve the accuracy of rainfall forecasting using PWV data include incorporating additional meteorological parameters like humidity, temperature, wind speed, and atmospheric pressure, localized model calibration, multi-station data integration, and advanced machine learning techniques. Real-time data, continuous updates, extensive cross-validation, and robustness testing can further enhance predictions. Collaborating with local meteorological agencies can refine models tailored to regional needs, improving flood forecasting and management efforts in Songkhla and similar regions.

According to the cumulative rainfall map from the Naval Research Laboratory of the United States, there was a continuous clustering of rainfall in the southern region of Thailand, particularly notable from October 31<sup>st</sup> to November 2<sup>nd</sup>.

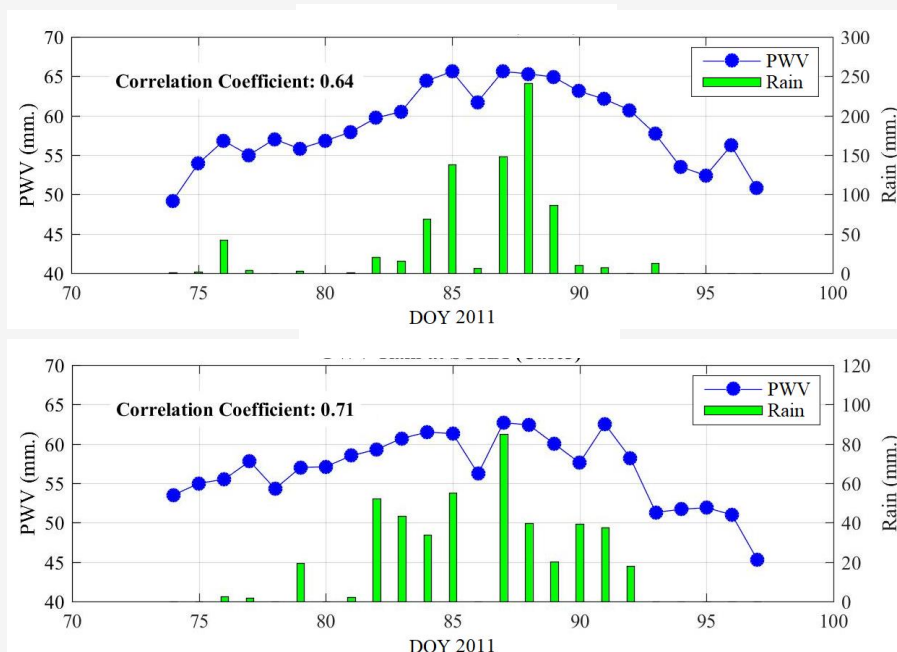
During this period, a thick cluster of rainfall was observed in the lower southern provinces, including Yala, Narathiwat, Songkhla, Pattani, Phatthalung, and Satun. Subsequently, from November 3<sup>rd</sup> to 4<sup>th</sup>, the rainfall cluster persisted but shifted northward towards provinces like Nakhon Si Thammarat, Surat Thani, and Chumphon. Following this, the rainfall intensity gradually diminished, only to re-emerge as a thick cluster again around November 9<sup>th</sup> to 10<sup>th</sup>, this time in provinces such as Nakhon Si Thammarat, Surat Thani, Chumphon, Krabi, and Phang Nga. Despite intermittent reductions, the rainfall clustering remained consistent until the end of the month (see Figure 5). The accumulated rainfall maps the Naval Research Laboratory provided show a significant discrepancy compared to the observed local rainfall data, particularly in Figures 4 and 5.



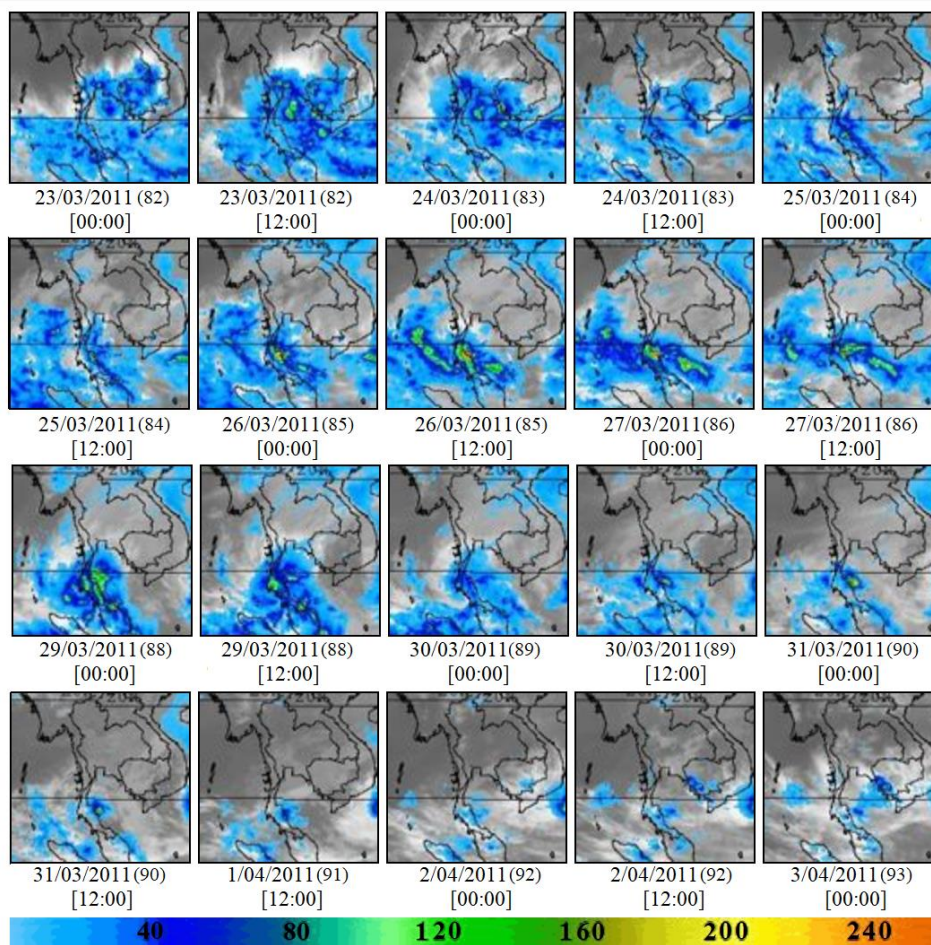
**Figure 5:** Accumulated rainfall SRTN-SOKA CASE2 [22]

While local data report high rainfall on DOY 305 followed by a substantial drop, the Naval Research Laboratory's maps indicate sustained high rainfall from DOY 305 to DOY 309. This inconsistency may be attributed to the low resolution of the rainfall maps, which may not capture localized rainfall variations as accurately as ground-based measurements. Addressing this issue, our study emphasizes the necessity for enhanced data assimilation techniques and acknowledges the limitations of global models in reflecting localized rainfall patterns. This approach aims to provide a more nuanced discussion on the reliability and interpretation of rainfall data, which is crucial for hydrology research and practical meteorological applications. In Case 3, focusing on the SRTN station in Surat Thani and the SOKA station in Songkhla in

the year 2011, the analysis revealed correlations between Precipitable Water Vapor (PWV) and rainfall during flood events. At the SRTN station in Surat Thani, a moderate correlation was observed, with a correlation coefficient ( $R$ ) of 0.64, indicating a moderate association between PWV and rainfall. Conversely, at the SOKA station in Songkhla, a stronger correlation was identified, with a correlation coefficient ( $R$ ) of 0.71, suggesting a more robust relationship between PWV and rainfall during flood events in 2011. These results, referring to Figure 6, highlight the variability in the strength of the relationship between PWV and rainfall across different stations in Surat Thani and Songkhla provinces during the specified year, emphasizing the influence of local meteorological conditions on precipitation dynamics during flood events.



**Figure 6:** Correlation PWV-Rain at SRTN-SOKA (Case3)



**Figure 7:** Accumulated rainfall SRTN-SOKA CASE3 [23]

According to the cumulative rainfall map from the Naval Research Laboratory of the United States, towards the end of March, there was a significant clustering of rainfall observed, particularly notable from March 26<sup>th</sup> to March 29<sup>th</sup>. During this period, there was a dense cluster of rainfall in the lower southern region of Thailand. This clustering of rainfall was particularly thick, indicating a substantial accumulation of precipitation in the lower southern part of the country (see Figure 7).

#### 4. Discussion

The investigation explored the relationship between Precipitable Water Vapor (PWV) and rainfall during flood events in Thailand. Table 1 highlights the average PWV levels one week before and after flood occurrences at the SOKA and SRTN stations, revealing a substantial increase compared to the corresponding period in the previous year. This significant elevation in PWV levels suggests its potential utility as a precursor to rainfall. The correlation between PWV variability during flood events and rainfall patterns also underscores the intricate interplay between meteorological parameters and PWV distribution. Notably, the consistent upward trend observed at the CHAN station aligns with the patterns seen at SOKA and SRTN, indicating its relevance in assessing PWV trends and forecasting rainfall events. Statistical analysis revealed significant correlations between PWV and rainfall, with correlation coefficients (R) of 0.78 for CHAN, 0.70 for SRTN, and 0.71 for SOKA, highlighting PWV as a valuable indicator for anticipating impending rainfall.

In the analysis of data from the SOKA station, Case 3 in 2011 shows a notably stronger correlation between PWV and rainfall compared to Case 2 in 2010. This difference highlights that the weather conditions 2011 were more favorable for a clear relationship between PWV and rainfall. Possible factors include variations in weather patterns, atmospheric dynamics, and the influence of broader climatic phenomena like the prominent La Niña event during 2010-2011. According to [16], La Niña increased rainfall without significant anomalies, leading to severe weather and widespread flooding due to heavy precipitation. Additionally, local elements such as topography, microclimate variations, and specific weather patterns in Songkhla during these periods likely influenced these correlations. Addressing these differences in the conclusion and discussion sections stresses the importance of considering temporal and regional

variations in meteorological factors when utilizing PWV data for effective flood prediction and management strategies.

Addressing the limitations of this study involves recognizing potential sources of error in PWV measurement, including instrumental inaccuracies, data processing inconsistencies, and the spatial and temporal limitations of GNSS stations. Local factors such as topography, microclimate variations, and specific weather patterns in Songkhla also influence the PWV-rainfall relationship. Strategies to mitigate these challenges include enhancing data assimilation techniques, calibrating models to local conditions, integrating multi-station data, employing advanced machine learning, and incorporating real-time updates. Collaboration with local meteorological agencies is crucial to refining models and improving flood forecasting and management efforts. These efforts ensure a nuanced discussion on PWV data reliability, which is essential for hydrology research and meteorological applications.

The variability in PWV during flood events underscores its potential as a tool for precipitation forecasting, enhancing flood management strategies. These findings offer actionable insights for policymakers and disaster management authorities to implement proactive measures based on PWV predictions. Future studies leveraging PWV could revolutionize precipitation forecasting in Thailand, providing timely information to protect lives and livelihoods. This research highlights PWV's critical role in understanding and addressing extreme weather challenges, paving the way for informed decision-making and climate-resilient development strategies.

#### 5. Conclusion

This study demonstrates a significant correlation between Precipitable Water Vapor (PWV) and rainfall during flood events in the provinces of Chanthaburi, Surat Thani, and Songkhla, Thailand, using data from the Global Navigation Satellite System (GNSS). The findings support that PWV can be a reliable leading indicator for anticipating heavy rainfall. A marked increase in average PWV was observed during flood events at the CHAN, SRTN, and SOKA stations, highlighting PWV's potential as a predictive rainfall and flood management tool. The strong correlation between PWV and rainfall patterns underscores the critical role of meteorological parameters in determining PWV distribution, which is crucial for preparing for and responding to heavy rainfall and flooding events.

When analyzed by specific flood events, the correlation between PWV and rainfall remained consistent, with Case 1 (2009) showing a correlation coefficient of 0.78 for CHAN, Case 2 (2010) showing correlation coefficients of 0.70 for SRTN and 0.27 for SOKA, and Case 3 (2011) showing correlation coefficients of 0.64 for SRTN and 0.71 for SOKA, affirming PWV's reliability as a meteorological parameter.

These results suggest important implications for improving precipitation forecasting and flood management strategies in the studied regions. Future research should include a broader network of GNSS CORS stations across Thailand to enhance the accuracy of PWV distribution predictions, offering a more comprehensive tool for forecasting heavy rainfall and managing disaster response. The benefits derived from this research include improved rainfall prediction capabilities and preparedness for flood events, potentially reducing the economic and social impacts of flooding in Thailand. Additionally, using PWV as a predictive tool for rainfall has the potential to develop more effective early warning systems, enhancing safety and security for lives and property.

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