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Research Article

Radar-Based Rainfall Estimation of Landfalling Tropical Storm "PABUK" 2019 over Southern Thailand

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Tropical storm PABUK developed from tropical depression first defined on 31 December 2018 in the lower South China Sea. It made landfall in Pak Phanang, Nakhon Si Thammarat province, southern Thailand. PABUK caused heavy rain and flash floods from 3 to 5 January 2019 (D1, D2, and D3) where the total rainfall reached 150–300 mm across 14 provinces of southern Thailand. This paper is aimed to investigate rainstorm properties and rainfall estimation of tropical storm PABUK with weather radar in southern Thailand. The radar data analysis in this study was to extract the radar reflectivity to study rainstorm properties of PABUK over 3 days along southern Thailand derived from the Thunderstorm Identification and Tracking Analysis and Nowcasting (TITAN) algorithm including 5 variables of duration, area, cloud-based height, maximum reflectivity, and speed in the data set. Based on the properties and frequency distribution of 2,557 rainstorms in D1, D2, and D3, rainstorms in D2 and D3 when PABUK made landfall over southern Thailand show a longer lifetime, higher reflectivity, and larger rain-cells as well as it was found efficient in terms of rainfall amount than in D1. In addition, the estimated rainfall using weather radar provides important information of the rainfall distribution for the analysis of the rainstorm as well. These analyses provide a context for interpreting the feasible rainfall estimates based on Z-R relationship during tropical storm PABUK that produced extreme floods in southern Thailand. A Z-R relationship in the form $Z = 104R^{1.5}$ provided acceptable statistical indicators, making it appropriate for radar estimated rainfall in case studies presented of tropical storm PABUK in southern Thailand. However, the result of this study should be improved to estimate precipitation in case of extremely heavy rainfall in tropical storm occurrence by using radar of southern Thailand and applied for applications of early warning systems.

1. Introduction

A large number of studies on rainstorm analysis obtained from capability for spatial and temporal storm profiles measurement of weather radar are widely used to detect the convective storms and study of convective storm structure [1–3] and also the process of the rainfall system itself by providing real-time regional information, and with the existence of long radar data sets, these data could be also applied for climatological applications. In addition, weather radar is also tool that combines meteorology and hydrology [4–6]; the meteorological information measured by radar are used for hydrological analysis as referred to Peng et al. [7], and they explained that the advantage of using radar for precipitation measurement is the coverage of a large area in real-time, and radars also experience difficulty in achieving an accurate estimation for hydrological applications. The single-polarization [3] and dual-polarization [8, 9] weather radar was used to study the relationship between radar reflectivity and rainfall rate which is developed for rainfall measurement by using the Z-R relationship. The uncertainty of radar rainfall estimation by using Z-R relationship was proposed by Chen et al. [10] and Gou et al. [11]. The developed Z-R relationships are needed in Thailand to provide a more systematic and comprehensive approach to achieve water management.

Applications of weather radar in Thailand are still limited mostly for meteorology and monitoring the weather routines. Not much work has been done in the field of hydrological and heavy rainfall cases. Finding rainfall intensity is one of the essential applications for weather radar in the process of hydrology, flood management, and early winning system in case of severe weather situation. For the purpose in radar rainfall estimation, the relationship between radar reflectivity and rainfall rate is developed for rainfall measurement by using the Z-R relationship. The Z-R relationship is highly dependent on the precipitation types and wind conditions such as convective, stratiform or mixed types, and deep convection [12–15]. Event type is one of the major influences of Z-R relationship that must be studied accordingly. Moreover, the location of areas and seasonal also plays an important factor in applying Z-R relationships to radar rainfall measurements [1, 16]. Most weather radars in Thailand are not calibrated for the Z-R relationship. As the results, the developed radar rainfall estimation in case of severe weather situation from tropical storm is needed in Thailand providing a more systematic and comprehensive approach to achieve in water management and also additionally to implement in flood warning purposes. Because the southern part of Thailand is a major economic tree plantation zone, especially fruits, oil palm, and rubber tree, it is almost in transition from water richness to water scarcity because of the increasing demands on this limited resource as well as there is no universal Z-R relationship that can be applied to all cases of rainfall events. Therefore, the focus of this paper will be on the optimization of Z-R relationships during tropical storm and heavy precipitation which were tuned to fit the rain gauge measurements that turn into inaccuracies over the central region of Thailand.

This article is structured as follows. The data and methodology section presents the overview of PABUK tropical cyclone, the technical characteristics of the radar used, radar data analyses, and the statistics for the analysis. This is followed with presenting the results of rainstorm properties and radar rainfall estimation during PABUK event, and the article closes with is a brief discussion about the conclusion reached.

2. Data and Methodology

2.1. Overview of PABUK Tropical Cyclone. Tropical storm PABUK, which has originated from the low-pressure zone in the South China Sea, developed from tropical depression first defined on 31 December 2018. This storm moved westward into the lower Gulf of Thailand, and it made landfall on 4 January 2019 over Phanang, Nakhon Si Thammarat province, at latitude of 8.2°N and longitude of 100.2°E. Maximum sustained wind is 75 kmhr^{-1}, and the storm was moving northwest at a speed of 18 kmhr^{-1}. PABUK became the first tropical storm to make landfall over southern Thailand since Linda in 1997. This affected the South with widespread heavy rainfalls, and torrential downpours are possible in much of southern area of Thailand from 3 to 5 January 2019 as follows:

(1) On 3 January 2019 (hereafter referred as D1) at 11.00 UTC, tropical storm "PABUK" was located 500 km southeast of Nakhon Si Thammarat province at the latitude of 6.5°N and longitude of 104.2°E with maximum sustained winds of 65 kmhr^{-1}. The storm was accelerated west-northwestward and entered the Gulf of Thailand which affected the lower part of southern Thailand with heavy rainfalls and some torrential downpours in Phatthalung, Songkhla, Pattani, Yala, and Narathiwat.

(2) On 4 January 2019 (hereafter as D2), the storm moved westward into the lower Gulf of Thailand, and it made landfall at 05 : 45 UTC over Phanang, Nakhon Si Thammarat province, at latitude of 8.2°N and longitude of 100.2°E with the maximum sustained wind of 75 kmhr^{-1}, and the storm was moving northwest at a speed of 18 kmhr^{-1}. It affected the east side of South with widespread heavy rainfall, strong winds, and severe conditions that cause forest runoffs and flash floods in Phetchaburi, Prachuap Khiri Khan, Chumphon, Surat Thani, Nakhon Si Thammarat, Phatthalung, Ranong, Phangnga, Phuket, Krabi, Trang, and Satun.

(3) On 5 January 2019 (hereafter as D3) at 17.00 UTC, tropical storm "PABUK" was due 5 km west of Takua Pa, Phangnga, with the latitude of 8.7°N and longitude of 104.2°E with the maximum sustained wind of 55 kmhr^{-1}; the storm was moving west-northwest slowly with the outbreaks of torrential downpours much of southern provinces including Phetchaburi, Prachuap Khiri Khan, Chumphon, Surat Thani, Nakhon Si Thammarat, Ranong, Phangnga, Phuket, and Krabi. PABUK then moved down to the Andaman Sea and weakened into a low-pressure cell during the same day and covered the Andaman Sea.

The influence of tropical storm PABUK caused strong wind shear, heavy rain, and flash floods from D1 to D3 where the accumulated rainfall reached 150–300 mm a day across 14 provinces of southern Thailand, especially in Nakhon Si Thammarat, Surat Thani, Chumphon, Ranong, Phatthalung, Songkhla, Pattani, Yala, and Narathiwat, the maximum rainfall in 24 hours reached 309.3 mm, and maximum wind speed was 89 kmhr^{-1} at Nakhon Si Thammarat province on D2. In addition, PABUK also results in rising sea levels and blowing into the shore as storm surge in the coastal region of upper southern region; the images of the damage caused by a tropical storm PABUK are as shown in Figure 1.

Figure 1: Strong wind shear and flooding caused by tropical Storm PABUK at first hit over Phanang, Nakhon Si) ammarat province, southern) ailand on D2 (image: REUTERS and https://news.mthai.com/).

2.2. Radar Data Analyses. The study area has been southern Thailand, characterized by a complex topography and directly influenced by the South China Sea and Indian Ocean (Figure 2). The C-Band Doppler Radar, which represents a good compromise between range and reflectivity that can provide rain detection up to a range of 240 km, from Thai Meteorological Department (TMD) was used in this study. The reflectivity data from Songkhla's radar located in the eastern coastline near the landfall of PABUK tropical storm were appropriately used to investigate the rainstorm properties and estimated radar rainfall that affected the southern region of Thailand. Radar is installed at Sathingpra District, Songkhla, at the elevation of 33 m MSL in southern Thailand as shown in Figure 2. The radar with EDGE™ software collected the reflectivity data as volume scan to the highest altitude up to 5 km provided in the universal flies (UF) format [17]. The files were obtained every 15 minutes up to the effective range of 240 km to the highest altitude up to 5 km provided in the volume format files for 4 elevation angles: 0.5°, 1.5°, 2.4°, and 3.4°, and a Doppler filter is applied to remove ground clutter and fixed echoes.

In order to characterize rainstorm properties, radar reflectivity data in horizontal polarization were run through TITAN and used the 30 dBZ reflectivity threshold to identify a convective storm cell before tracking their movement as referred to Dixon and Wiener [18]; Johnson et al. [19], and Potts et al. [20]. All of rainstorms were selected and analyzed by the dataset from the criteria as suggestion by Chantraket et al., [1] including their 5 properties as exhibited in Table 1. However, it may be mentioned that in this study, only those rainstorms are considered whose rain centers are located in the effective range of 240 km of Songkhla's radar. The event numbers differed in each day; these data were then analyzed to express properties of individual rainstorms. The total of 2,557 rainstorm events were chosen from D1 (1,014 rainstorms), D2 (962 rainstorms), and D3 (581 rainstorms), respectively, during occurred PABUK tropical cyclone. The example case of rainstorm events from TITAN analysis is presented in Figure 3, and the preliminary of statistical analysis of all properties is illustrated as Table 2.

In order to estimate radar rainfall, the relationship between radar reflectivity and rainfall rate which is developed for rainfall measurement was used as explained in the following equation:

$$Z = aR^b, \quad (1)$$

where a and b are the relationship parameters, Z is the radar reflectivity in mm^6m^{-3}, and R is the intensity of precipitation mmh^{-1}.

The rainfall events were used to obtain the appropriated Z-R relationship for tropical storm in southern Thailand as well as to test an accuracy of the proposed radar rainfall estimation based on different Z-R relationships as referred to Kirtsaeng and Chantraket [16] of Songkhla's radar of $Z = 104R^{1.5}$, $Z = 162R^{1.5}$, and $Z = 184R^{1.5}$ and the operational Z-R relationships of TMD $Z = 300R^{1.4}$ as referred for all rain types especially for deep convective [21, 22]. In order to evaluate the suitable Z-R relationship for tropical storm of PABUK, their measurement wascompared with the precipitation recorded by the rain gauges from automatic meteorological stations of Hydro Informatics Institute (HII) and TMD. The study was performed by using 24-hour accumulations of 156 rain gauges in and around southern regions in the coverage of radar effective range (see Figure 2) having been scrutinized during D1 to D3. These data were procured from the (i) 129 stations of HII and (ii) 27 stations of TMD. After procurement of 24-hour accumulations from different sources, these were subjected to extensive quality control tests to remove gross errors, archival errors, and reformatting problem; however, the suspected data were checked for validation from different reliable sources. The study was carried out using 24-hour accumulations, comparing with estimated rain accumulation from Z-R relationship that occupied the position of rain gauges. Rain gauge measurement and radar estimate of 24-hour accumulations greater than 1.0 mm and less than 300 mm were considered to be valid. Daily rainfall distribution in southern Thailand caused by tropical storm PABUK during D1, D2, and D3 is shown in Figure 4.

The statistical indexes used to evaluate the different of estimated rain accumulation from Z-R relationship related with the rain gauges as recommended by [23] are as follows.

Root mean square error (RMSE) is as follows:

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(R_i - G_i\right)^2}. \quad (2)$$

Mean error (ME) is as follows:

$$\text{ME} = \frac{1}{n}\sum_{i=1}^{N}\left(R_i - G_i\right). \quad (3)$$

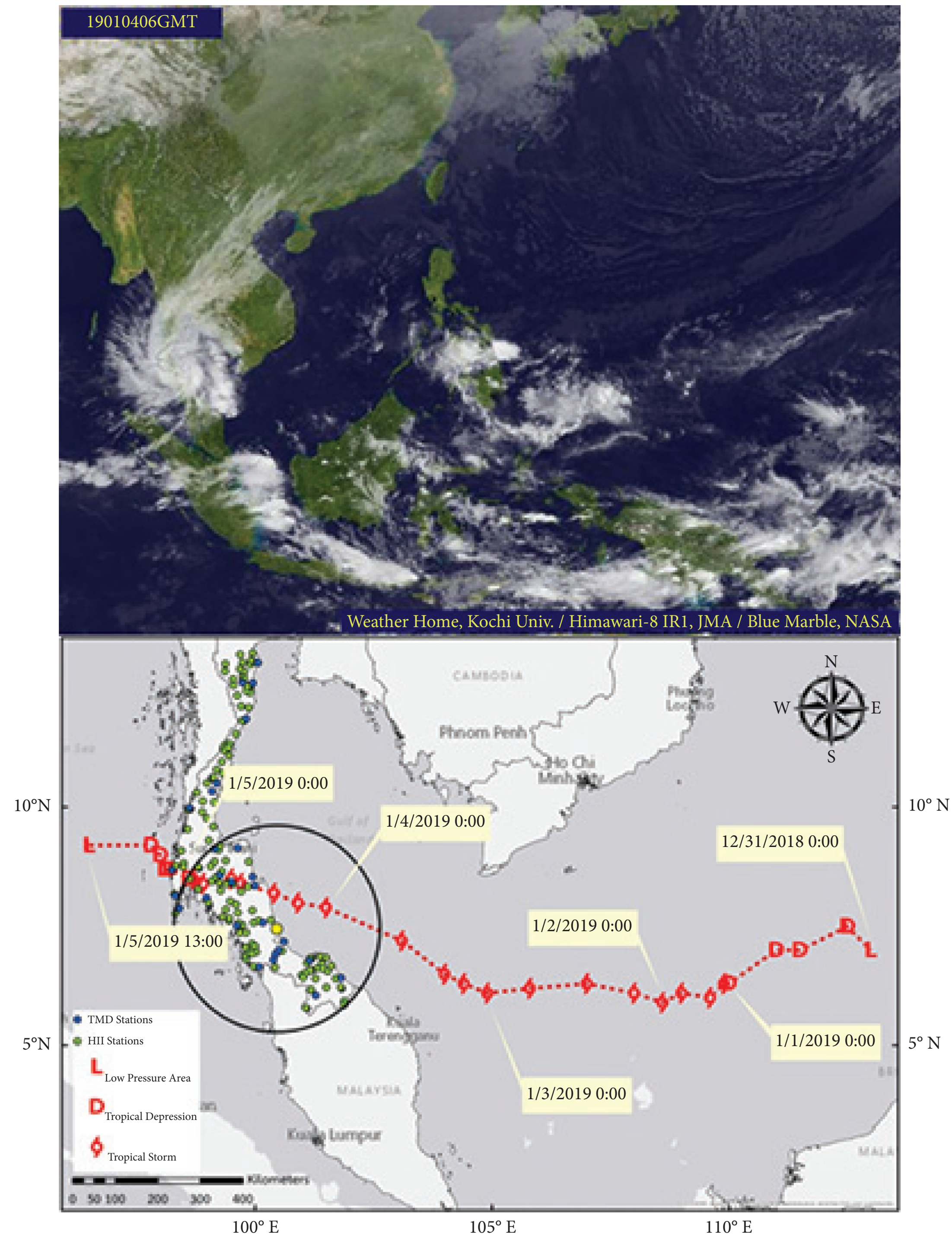
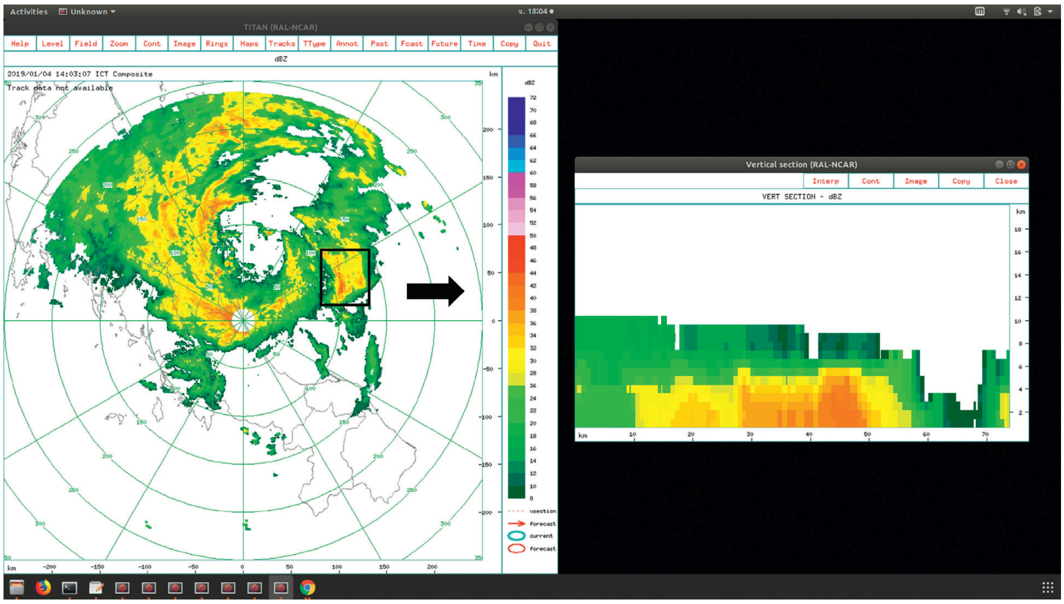


Figure 2: Tropical storm PABUK developed from a tropical depression and being placed at 6 h intervals and as observed during D3 at 0600 UTC time by Japan's Himawari-8 satellite. Image credit: JMA (Japan meteorological agency).

Table 1: Radar-obtained storm characteristics from TITAN and their units.

Rainstorm properties	Variables	Units
(1) Mean storm duration	SDUR	Hours
(2) Mean storm-based	SBAS	km MSL
(3) Maximum envelope area	SARE	km^2
(4) Maximum reflectivity	SREF	dBZ
(5) Mean speed	SVEL	$kmhr^{-1}$



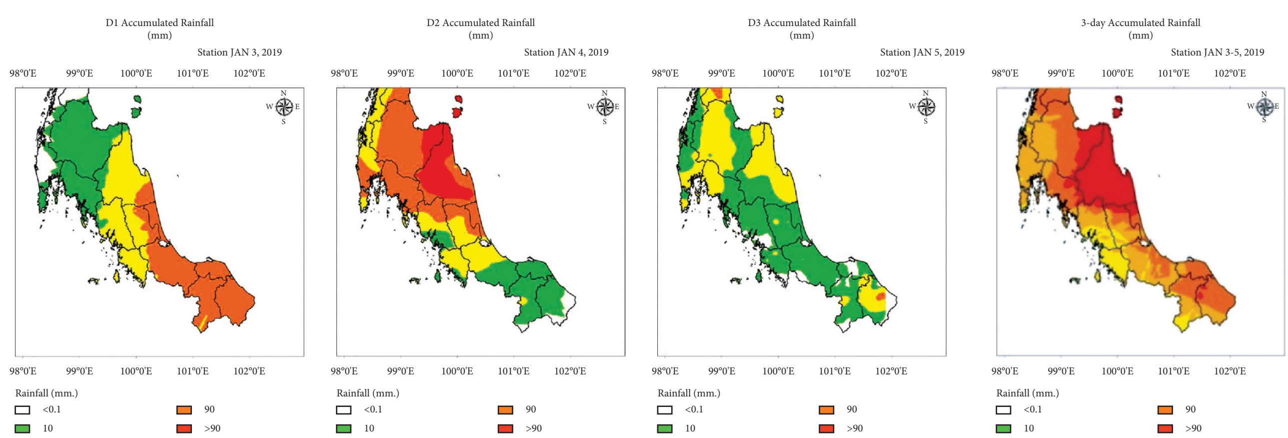
(a) (b)

Figure 3: Some case of rainstorm events obtained from TITAN analysis of Songkhla's radar on D2 at 14 : 03 UTC: (a) TITAN analysis image and (b) cross section of selected rainstorm.

Table 2: The storm properties during D1, D2, and D3 of PABUK event in southern Thailand.

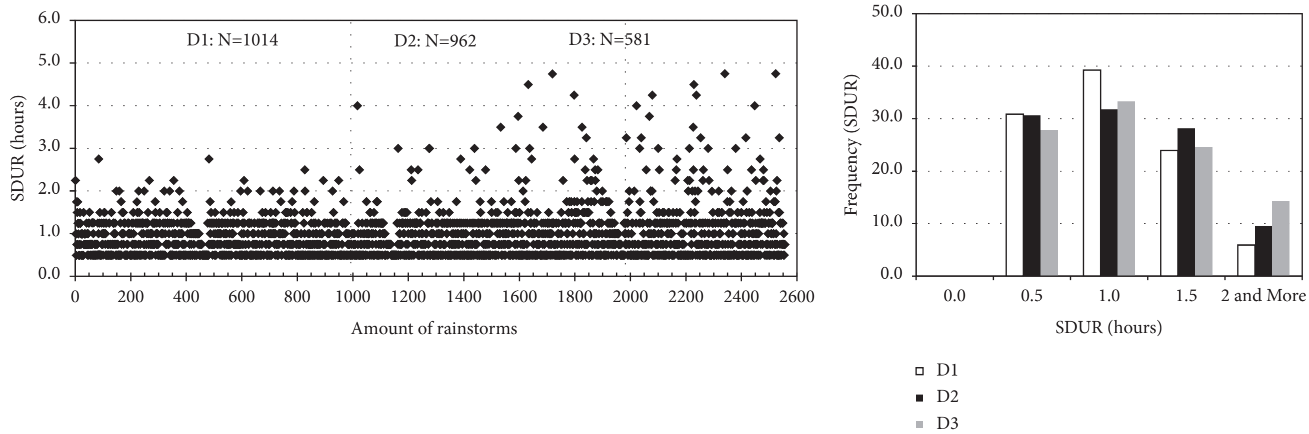
	SDUR Hours				SBAS km MSL				SREF dBZ				SARE km^2				SVEL $kmhr^{-1}$			
	D1	D2	D3	D1-D3	D1	D2	D3	D1-D3	D1	D2	D3	D1-D3	D1	D2	D3	D1-D3	D1	D2	D3	D1-D3
Mean	0.9	0.9	1.0	0.9	2.0	1.8	1.9	1.9	35.0	38.6	43.5	38.3	52.0	55.8	46.4	52.2	23.1	22.5	18.2	21.8
SD	0.4	0.5	0.7	0.5	0.9	0.9	0.9	0.9	5.2	6.9	8.3	7.4	112.9	138.7	68.1	115.5	13.4	13.5	11.5	13.2
Min	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.6	30.0	30.0	30.0	30.0	3.4	4.5	4.5	3.4	0.0	0.0	0.0	0.0
Max	2.8	4.7	4.8	4.8	3.6	3.6	3.6	3.6	61.0	62.0	67.5	67.5	2666.3	3359.3	737.4	3359.3	62.3	114.5	56.0	114.5

D1: $N = 1014$ events, D2: $N = 962$ events, and D3: $N = 581$ events.



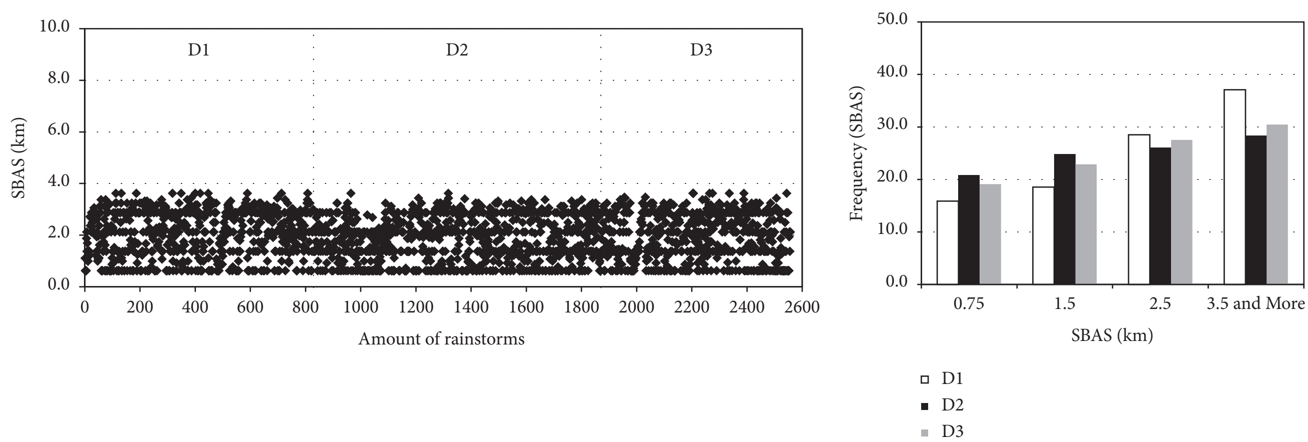
(a) (b) (c) (d)

Figure 4: Rainfall distribution of 24-hour accumulations in southern Thailand caused by tropical storm PABUK through (a) D1, (b) D2, and, (c) D3 and (d) 3-day accumulated rainfall during D1 to D3.



(a) (b)

Figure 5: The rainstorm duration (a) and frequency distribution (b) during D1, D2, and D3.



(a) (b)

Figure 6: The rainstorm bases (a) and frequency distribution (b) during D1, D2, and D3.

Mean absolute error (MAE) is as follows:

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{N}\left|R_i - G_i\right|. \tag{4}$$

Bias is as follows:

$$B = \frac{\sum_{i=1}^{N} G_i}{\sum_{i=1}^{N} R_i}, \tag{5}$$

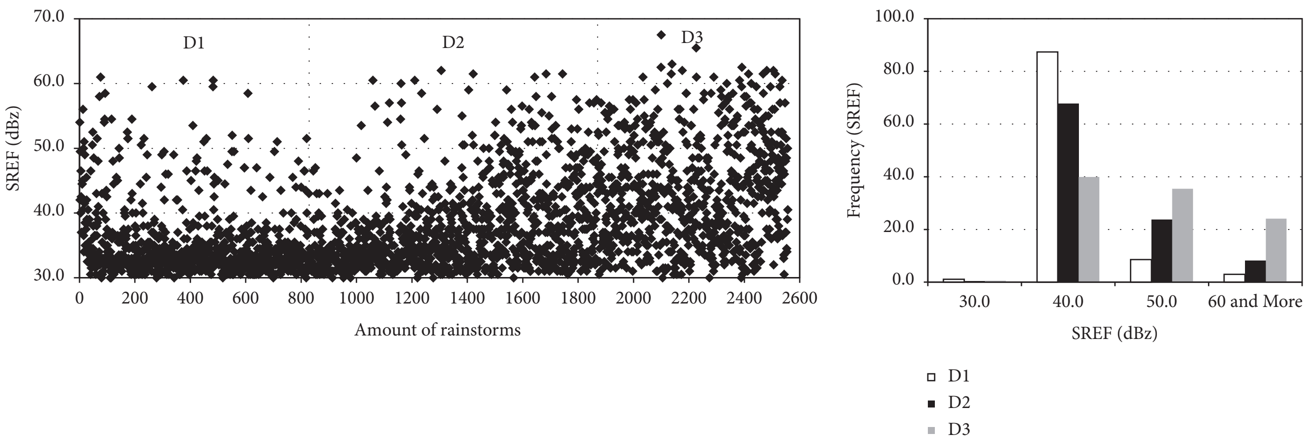
where G is 24-hour accumulations of rain gauges at station i in mm, R is 24-hour accumulations of radar rainfall computed using Z-R relationship at the point with coincided to rain gauge station i in mm, and N is the number of precipitation records.

Several Z-R relationships would be specified by the calculation of equations (2) to (5). Whichever relation provides the minimum of the four statistical measures will be selected as the most suitable relations for the study.

3. Result and Discussion

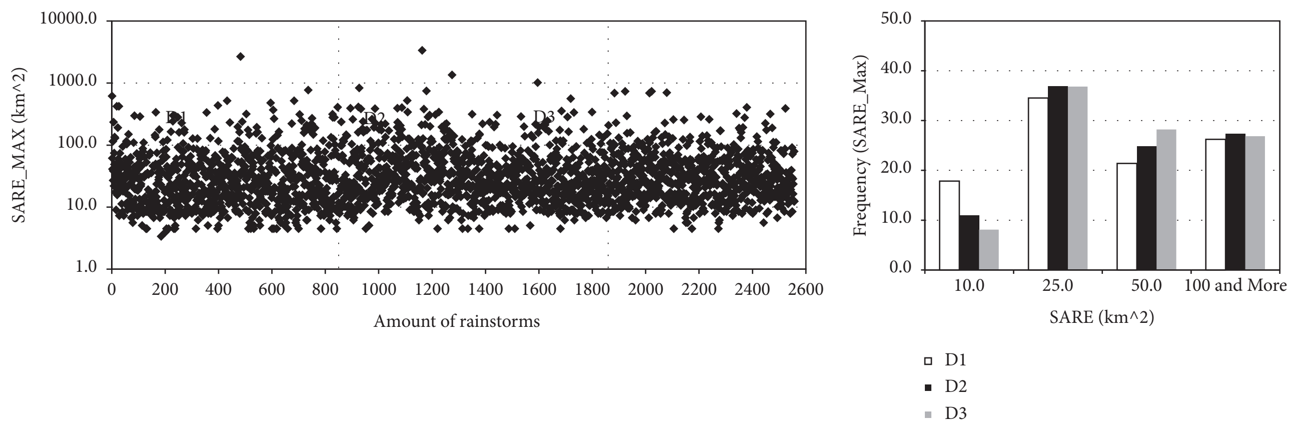
3.1. Rainstorm Properties of Tropical Storm PABUK from D1, D2, and D3

3.1.1. Rainstorm Duration (SDUR). SDUR is the time elapsed from the first radar reflectivity of 30 dBZ until the disappearance of precipitation. This study revealed that the average individual SDUR during D1 to D3 was around 0.9 to 1 hour, and almost all SDURs in D1 were less than 2 hours as in D2 and D3 tended to be longer duration than D1 as 1 to 3 hours. It is implied that the longer SDUR in D2 and D3 would extend the potential of rainfall intensity near the center of tropical storm PABUK in accordance with extremely heavy rainfall in D2 and D3 of rain gauge measurement when the rainstorm made landfall over southern Thailand. The time series and frequency distribution of SDUR on D1 to D3 are illustrated in Figure 5.



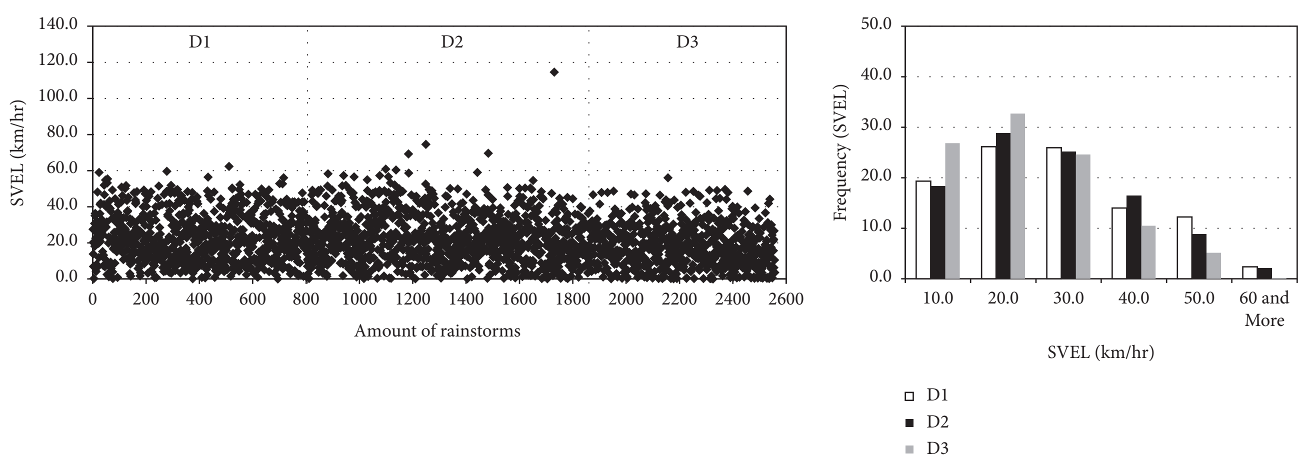
(a) (b)

Figure 7: The rainstorm reflectivity (a) and frequency distribution (b) during D1, D2, and D3.



(a) (b)

Figure 8: The rainstorm area (a) and frequency distribution (b) during D1, D2, and D3.



(a) (b)

Figure 9: The rainstorm speed (a) and frequency distribution (b) during D1, D2, and D3.

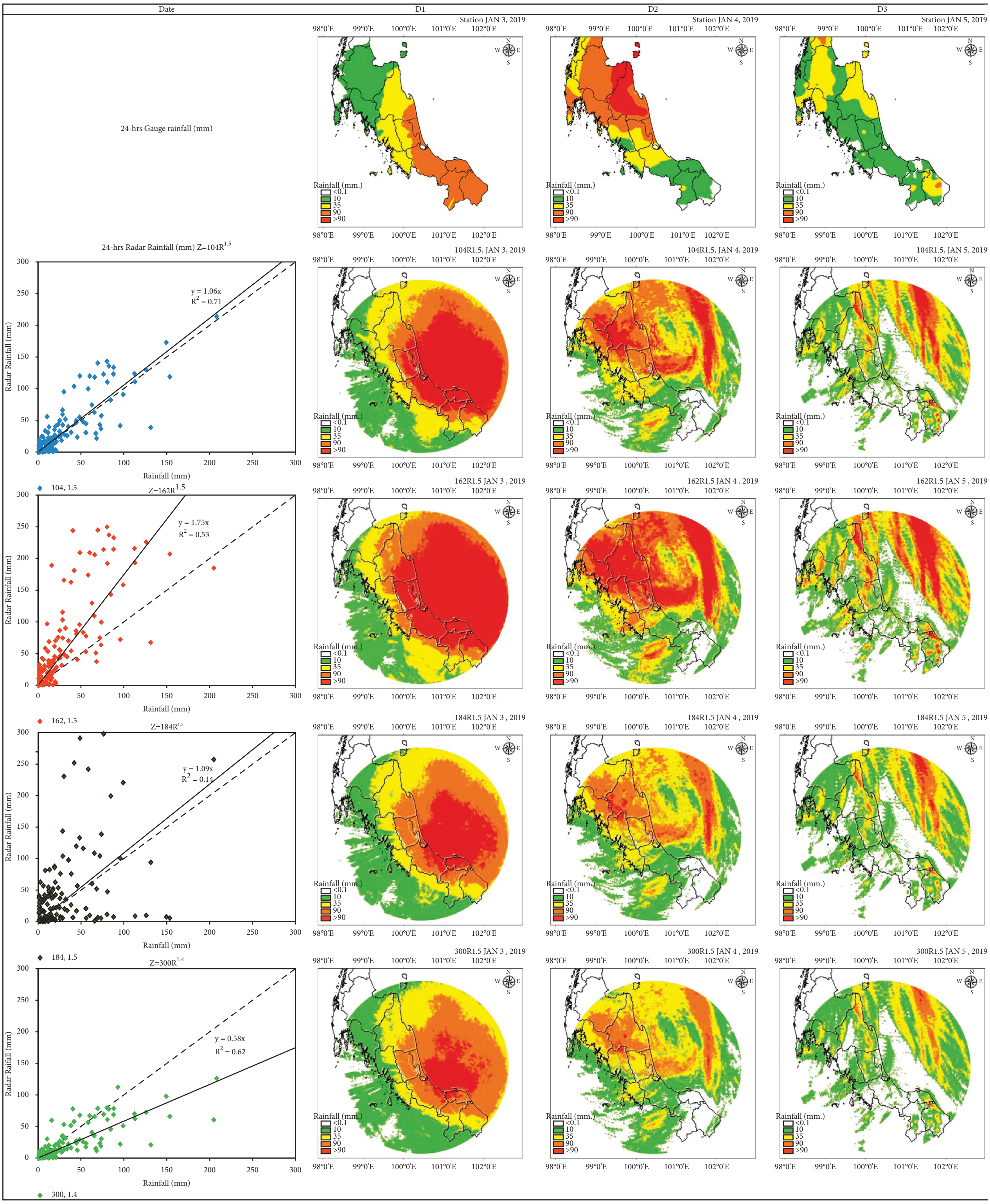


Figure 10: (a) Scatter plot between measured and estimated rainfall rate based on the different Z-R relationship of $Z = 184R^{1.5}$, $Z = 104R^{1.5}$, $Z = 162R^{1.5}$, and $Z = 300R^{1.4}$ and (b) time series plot of gauge rainfall and radar rainfall during D1, D2, and D3 by using the different Z-R relationship of $Z = 184R^{1.5}$, $Z = 104R^{1.5}$, $Z = 162R^{1.5}$, and $Z = 300R^{1.4}$.

3.1.2. Rainstorm Bases (SBAS). The SBAS show the minimum height of radar reflectivity, as the minimum reflectivity threshold and altitude are determined as 30 dBZ and 0.6 km, respectively. The results of this study showed that an average of SBAS is quite similar in D1, D2, and D3; between 1.8 and 2.0 km MSL, all events of occurred rainstorms are lower than

Table 3: Comparisons of the statistical measures gained from the different Z-R relationships of $Z = 184R^{1.5}$, $Z = 104R^{1.5}$, $Z = 162R^{1.5}$, and $Z = 300R^{1.4}$.

Z-R relationships	ME (mm)	RMSE (mm)	MAE (mm)	BIAS (G/R)
$Z = 104R^{1.5}$(NEM)	**−4.00**	**21.27**	**12.46**	**0.87**
$Z = 162R^{1.5}$(BULK)	−26.33	53.40	30.10	0.48
$Z = 184R^{1.5}$(SWM)	−12.06	54.77	30.48	0.67
$Z = 300R^{1.4}$(WSR)	9.34	24.38	12.94	1.52

4 km during PABUK occurrence. The time series and frequency distribution of SBAS on D1 to D3 are illustrated in Figure 6.

3.1.3. Rainstorm Reflectivity (SREF). The result from this study shows that on average maximum value, storm's reflectivity peaks that occurred during PABUK are distinguished among three days and tend to be higher SREF from D1, D2, and D3 as 35.0 dBZ, 38.6 dBZ, and 43.5 dBZ, respectively. Furthermore, the maximum SREF was found as a stronger reflectivity more than 60 dBz which corresponds to the precipitation intensity and the development of PABUK tropical cyclone during D1 to D3 as well. The variation of SREF along three days in PABUK period is presented in Figure 7.

3.1.4. Rainstorm Area (SARE). The average SARE during PABUK period shows difference among D1, D2, and D3. The largest SARE from individual rainstorm is shown in D2 that is approximately 55.8 km^2. It is seen that the area of individual rainstorms of D2 when PABUK made landfall over Nakhon Si Thammarat province was found to be more potential rainstorms than D1 and D3 according to the extremely heavy rainfall in D2 occurred near the landfall point and inland of southern part. The D2 rainstorm composes of several large cells as well as they can also lead to larger areas of precipitation. The variation of these properties along three days in PABUK period is presented in Figure 8.

3.1.5. Rainstorm Speed (SVEL). The TITAN algorithm can provide the information of storm tracking and its movement. The results obtained from this study show that the average SVEL of D1, D2, and D3 was 23.1 $kmhr^{-1}$, 22.5 $kmhr^{-1}$, and 18.2 $kmhr^{-1}$, respectively. Most of SVEL has tend to be at lower speed when landfalling and passing through the land of southern Thailand. Investigating the maximum speed in D1, D2, and D3 as illustrated in Table 2, it is found that maximum SVEL of individual rainstorms was observed in D2 consistently with the report of maximum sustained wind during PABUK occurred period as well. The time series and frequency distribution of SVEL on D1 to D3 are illustrated in Figure 9.

3.2. Radar Rainfall Estimation. The radar estimated rainfall during PABUK landfall period was analyzed by the step as explained in the previous section. The result of estimated rainfall accumulation using Z-R relationship in four trials of (1) $Z = 184R^{1.5}$, (2) $Z = 104R^{1.5}$, (3) $Z = 162R^{1.5}$, and (4) $Z = 300R^{1.4}$ is compared. The comparison of the 24 hr accumulated radar rainfall and the 24 hr accumulated gauge rainfall using the four trials of Z-R relationship is presented in Figure 10, and the statistical measures comparing these two sets of data are also calculated and summarized in Table 3.

Figure 10 shows the images of estimated daily radar rainfall attained from four Z-R relationships in D1, D2, and D3 and the scatter plot of the 24 hr accumulation of estimated radar rainfall attained from the different Z-R relationships and 24 hr accumulated gauge rainfall during D1 to D3. The estimated daily radar rainfall using the four trails of relation in D1, D2, and D3 was plotted as shown in the left side of radar images. From the scatter plot, it can be noted that the estimated radar rainfall accumulation is mostly higher than accumulated rain gauges except for $Z = 300R^{1.4}$ and also shows that $Z = 104R^{1.5}$ can provide the closest compared with the scatter plot of the other relations.

An agreement between estimated radar and gauge rainfall was examined using the statistical measures resulting from the four trials of Z-R relationships. The results show that the $Z = 104R^{1.5}$ is acceptable for overall statistical measures, with minimum of the four statistical measures, RMSE, ME, MAE, and BIAS, between the estimated radar and calculated rain gauge rainfall for the data sets in D1, D2, and D3. The calibrated Z-R relationship of $Z = 104R^{1.5}$ is therefore appropriate to be used for an estimation of accumulated radar rainfall in the tropical storm of PABUK.

4. Conclusions

The study presented the physical properties of rainstorm and radar-based rainfall estimation during tropical storm PABUK moving into the lower Gulf of Thailand and making landfall over southern Thailand which affected the southern regions with widespread heavy rainfall and flash floods. Derived from the data set of radar reflectivity and rain gauges during three days of PABUK, all storm properties were analyzed with TITAN, and estimated radar rainfall specified the appropriated Z-R relationship by the selected statistical measures. The results are shown as follows:

(1) Three days (D1, D2, and D3) during the tropical storm of PABUK in order to investigate rainstorm of southern Thailand obtained the 5 properties of rainstorms by using TITAN, which provided the important analysis tool to identify rainstorms and their movement in this study. It is revealed that rainstorms were found to be the most effective clouds over southern region. In accordance with the

characteristics of rainstorms, it can be seen that rainstorms in D2 and D3 when PABUK made landfall over Nakhon Si Thammarat province, southern Thailand, show a longer lifetime, higher reflectivity, and larger rain-cells as well as it was found efficient in terms of rainfall amount than in D1 consistently with the records of high precipitation depth in southern in that periods.

(2) The appropriated Z-R relationship acceptable for estimated radar rainfall during the tropical storm of PABUK in southern Thailand is $Z = 104\mathrm{R}^{1.5}$, which provided the minimum of the four statistical measures (RMSE, ME, MAE, and BIAS) so far as the southern basin is concerned. The results should be especially useful in urban design problems as well as in hydrologic design problems during unusual cases such as extremely heavy rainfall from tropical storm on the southern basin.

(3) These results are provided to assess the planning of water resources on a probability in a particular region or a basin and made to provide improvement of hydrometeorological relations that are pertinent to hydrological applications in the southern region and also capable of adapting to the other parts of Thailand. Relationships presented are subject to modification as additional data are collected in the heavy windy rainstorms, and further research is conducted.

Data Availability

All data used in the study are included in the manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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