AN ANALYSIS OF SEASONAL THUNDERSTORM CLOUD DISTRIBUTION AND ITS RELATION TO RAINFALL OCCURRENCE IN THAILAND USING REMOTELY SENSED DATA

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Abstract

The main objective of this study is to analyze the relationship between rainfall intensity and the associated cloud properties which are cloud top temperature (CTT) and cloud cover in Thailand based on some selected case studies during years 2006 and 2007. In addition, the classified cloud data were also applied to the investigation of seasonal cloud and rainfall distribution during those specified years. To assist the efficient derivation of cloud top temperature maps, the automatic cloud classification model for the thermal infrared (TIR) images of the MTSAT-1R satellite was developed and applied as main tool for CTT mapping in the study. And to reduce possible confusion between high clouds and rain clouds (cumulonimbus), the high clouds were filtered off first using the split-window technique under the given thresholds. The classified CTT maps include all clouds with CTT less than 10°C and, as a consequence, most warm clouds and cold clouds are depicted on the obtained maps. The analysis of seasonal cloud and rainfall distribution indicates that patterns of their distribution in Thailand are the product of the combined effects among several main driving factors. In summer, these are the local convective system, the cold air mass, the monsoon trough, the westerly wind, and the low pressure area from the ocean. In the rainy season, these are the monsoon trough, the southwest monsoon, and the tropical cyclone and low pressure area from the ocean. And in winter, these are the cold air mass, the northeast monsoon (for the south), and local convection. The amount of total daily rainfall has a high correlation with the amount of cloud cover area seen each day, with $r^2 > 0.8$ in all cases especially heavy rainfall (e.g. > 80 mm) or on the hail days (with $r^2 = 0.8915$).

Keywords: Satellite cloud classification, thunderstorm cloud classification, estimate rainfall, MTSAT-1R, split windows

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Introduction

Rational

Cloud and rain are considered key components of the global hydrologic cycle that regulates the circulating mechanism of water in nature. Clouds are the original source of rain which is crucial for the daily lives of the majority of the population on the Earth, especially the farmers. As a result, the knowledge of cloud structure and distribution is essential for the understanding of rainfall pattern and climate changes in the interested area. At present, the most effective method to study cloud and rainfall distribution on a regional or country scale is by using observed data from the weather satellites. These satellites have been specifically designed for the observation and measurement of the structure and gaseous components of the Earth's atmosphere as well as the important atmospheric phenomena such as rain, cloud, wind, thunderstorm, or hurricane.

Typically, the application of satellite imagery to weather study in Thailand is still rare and mostly focused on the prediction of the rain rate from CTT derived from the TIR satellite images. However, most studies have focused mainly on the analysis of the cloud/rainfall relationship based on data at a few selected stations. Therefore, in principle, their obtained results still cannot explain the variety of the cloud and rainfall relationships in the country as a whole. To gain more knowledge of the relationship in a wider scope, data from more stations covering a wider area and in a longer time-span of rain/cloud records are needed, which is significantly fulfilled in this study. In addition, in this research, the cloud data derived from TIR satellite images are also applied to the study of seasonal weather variations observed in years 2006 and 2007.

Study Area

The study area was covered Thailand's boundary with located in the tropical zone within the latitudes of 05° 37' to 20° 27'N and longitudes of 97° 22' to 105° 37'E with approximately 513,115 km^2 in area cover.

Methodology

Conceptual Framework

The main objective of this study is to analyze the relationship between rainfall intensity and the associated cloud properties (CTT and cloud cover area) in Thailand based on the selected case studies occurring in 2006 and 2007. To achieve this goal, three main steps of the work procedure were planned and implemented:

(1) Development of the automatic cloud mapping and classification model for use with MTSAT-1R imagery,

(2) Examination of the seasonal rainfall and cloud cover distribution patterns during the selected years, and

(3) Analysis on the relationship between rainfall intensity and cloud properties (CTT and cloud cover area) based on the chosen case studies.

Figure 1 presents a diagram of the work procedure mentioned above where its first part (model development) is described in detail in this topic while information about the other two parts is further described in the results. Information about all used data and their original source is given in Table 1.

This work needs large numbers of the classified cloud distribution and CTT maps over the entire country in the analysis process but the proper tools to operate this task effectively were still to be found. As a consequence, at the beginning of the research period, most of the time was devoted to the development of such a tool based on the application of several existing computer programs like MATLAB, SML, and ERDAS Macro. The result is the cloud classification model for MTSAT-1R imagery over Thailand as needed (see the Analyzing Process topic for details).

Data Collection and Map Data Preparation

All needed data for the study are described in Table 1 along with the original source of the referred data. However, most data have to be modified, or enhanced, and transformed into proper formats that are capable of being used by the processing program or models. This is

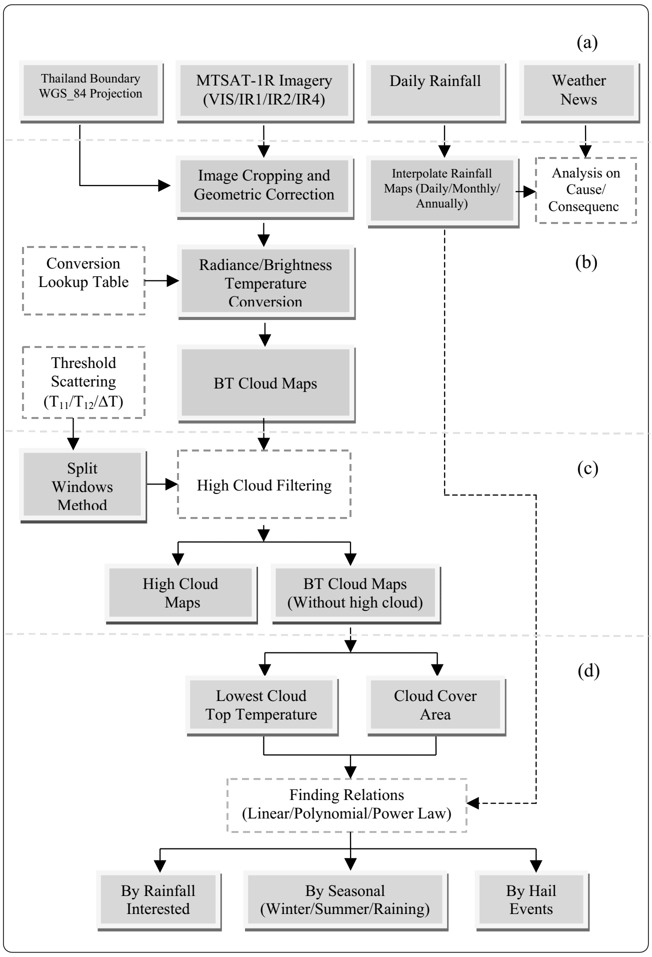


Figure 1. Flow chart of the study divided into 4 principal parts: (a) data collection (b) data map preparation, (c) cloud model development and (d) analysis and reporting

Table 1. Information of the data usage

Data type	Raw data format	Input format	Original source
Rainfall	Daily record from 116 TMD stations	Interpolated map (using IDW method)	Thai Meteorological Department (TMD)
Satellite imagery	MTSAT-1R (1 VIS and 4 TIR bands)	Cloud cover area and CTT maps	Kochi University, Japan
Boundary map	Province polygon	Country boundary	Department of Environmental Quality Promotion (DEQP)
Weather news	Official report	Details of the events	TMD, Department of Disaster Prevention and Mitigation (DDPM)

called map data preparation and details are as follows:

Rainfall Map

The first stage of the analysis process that was performed was the examination of rainfall patterns over Thailand compared between years 2006 and 2007 based on the generated monthly, quarterly, and annual rainfall maps of those years. These maps were created by the interpolation of rainfall records from 116 weather stations located around the country using the inverse distance weighted (IDW) interpolation method. Rainfall isohytal maps were created from rainfall records of 116 weather stations in the year of 2006 and 2007.

The daily rainfall data were subsequently accumulated to produce rainfall map at specific time periods required; e.g. daily, monthly or annual. To assist the qualitative analysis, rainfall data were divided into several classes to represent different zones of intensity level on the rainfall maps.

Cloud Cover Map

The cloud cover maps for some selected dates or periods, were also prepared based on raw data of MTSAT-1R satellite images in the visible and infrared regions, which can be downloaded from the website of Kochi University in Japan: http://weather.is.kochi/archive-e.html, under supervision. However, for the present study, only hourly image files were available for the download with ancillary data of the image include but are not limited to hour/date/year being taken or spectral bands.

All 5 bands of the VISSR sensor (1 visible and 4 TIR) are available for the download. The spatial resolution of the visible image is about 1 km (nadir) and of the TIR image is about 4 km (nadir). An example of the satellite's visible image is shown in Figure 2.

Before being put in use, the original satellite images must be cropped to separate the portion of area over Thailand for further study using the MATLAB program. The ERDAS program based on the WGS-84 projection then geometrically corrected these images and the country's boundaries were then added to the cropped image. The boundary locations were derived by dissolving the province polygon provided by the Department of Environmental Quality Promotion (DEQP).

The brightness values in the gray scale 0-255 for TIR images were subsequently converted into the equivalent brightness temperature (BT) (in Kelvin unit) based on the standard look-up tables for the proper conversion of each TIR band provided by the satellite's responsible agency- the Japan Aerospace Exploration Agency (JAXA). The BT images are needed for the classification of cloud types, especially the heavy-rain cloud (cumulonimbus) and cold/high cloud (e.g. cirrus), by conventional methods like the bi-spectral (along with VIS image) or split-window technique.

However, to evaluate the relationship between rainfall and CTT, the non-precipitating cold clouds, like cirrus, must be screened off first otherwise they may be mistakenly classed as being rain-bearing cumulonimbus as their normal CTTs are rather indifferent. All the aforementioned procedure can be operated automatically using the developed model that is discussed later in the heading Radiance Conversion for BT Mapping topic.

Analysis Process

The first step of the planned analyzing process in this research was to examine the variation in patterns of the seasonal rainfall and cloud distribution over Thailand in the selected

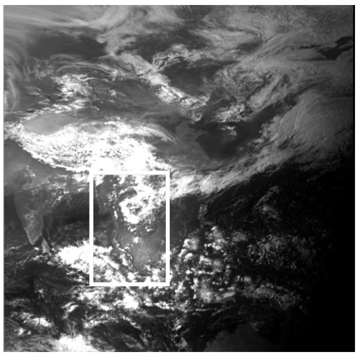


Figure 2. MTSAT-1R VIS image over the Pacific Ocean on 25 April 2007 Source: Kochi University (http://weather.is.kochi/archive-e.html)

years (2006 and 2007), and also to identify the causal factors that influence the appearance of those observed rain and cloud maps. Priority was given to the main factors that are believed to dominate pattern of rainfall found in Thailand, especially the monsoon systems.

The work in this part was focused on analyzing the seasonal cloud and rainfall distribution patterns as a whole based on their observed data during the years. For the rainfall, these are accumulated rainfall maps on a monthly, seasonal, and annual basis. But for the cloud cover, these are temporal classified cloud maps during some chosen period (about 5 days) in each season (summer, rainy, and winter).

The second task was to analyze the relationship between rainfall intensity and cloud properties (CTT and cloud cover area) based on some chosen case studies. The used rainfall data (for each case) were obtained from the 116 TMD stations mentioned earlier and the corresponding CTT maps were derived from the developed model. The analysis was separated into 3 broad scenarios based on season, region, and rainfall intensity. Particular interest was given to the severe rainfall from the cumulonimbus cloud. The relationship was explained in proper linear form, polynomial form, or power-law regression form that most fit.

Focus of the study was also placed upon the hail events, which are good indicators for the presence of severe thunderstorms (from the cumulonimbus cloud). Information on hail events was gathered from official reports issued by the Thai Meteorological Department (TMD) and the Department of Disaster Prevention and Mitigation (DDPM) in 2006 and 2007.

Development of Automatic Cloud Classification Model

This study needed to use the large numbers of the classified cloud distribution and CTT maps over the entire country in the analysis process. There were 3 main steps in the formation of this required cloud classification model after the original satellite image files were downloaded from the host website (at Kochi University) which were:

(1) Cropping and geometric correction of the Thailand portion in the image,

(2) Conversion from radiance files into an equivalent BT file, and

(3) Classification of cloud types using the brightness temperature map.

Cropping and Geometric Correction of Thailand Portion

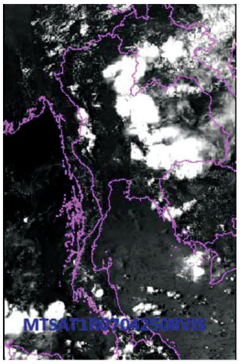
This study concerns only the rainfall and cloud distribution over Thailand's territory while the original MTSAT-1R satellite images cover all the Pacific regions, where Thailand is located on the far left of the image, as seen in Figure 2. As a result, all the downloaded images must be cropped to reduce their size to cover the Thailand portion only. This was achieved by using the MATLAB cropping module that is able to operate the cropping file by file through the entire source directory. The destination directory, band preference, or cropping location can also be specified on the module through the code-writing process.

To crop the Thailand portion off from the whole image, 4 specific coordinates close to the Thai borders were chosen and listed as positions A, B, C, and D, where their respective coordinates are: A (96°E, 22°N); B (107°E, 22°N); C (96°E, 5°S); and D (107°E, 5°S). The cropped image now has 220 x 340 pixels. Examples of the cropped image files over Thailand are shown in Figure 3.

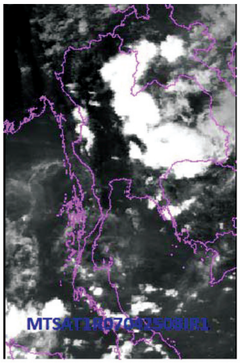
These images were then geometrically corrected using the ERDAS program and based on the WGS-84 lat/long projection and the country's boundaries were then added to the cropped image. The boundary was derived from the province polygon provided by the DEQP.

Radiance Conversion for BT Mapping

To classify the cloud types on the satellite images, knowledge of the CTT is necessary. For MTSAT-TIR imagery, this CTT map could be generated directly by using the standard look-up table for the radiance/BT conversion provided for each individual image (Table 3 and Figure 4) for examples. The conversion table was formulated based on the Planck function and the sensor's spectral response functions from which the approximated conversion formula is given as follows (Meteorological Satellite Center, 2009):



(a)



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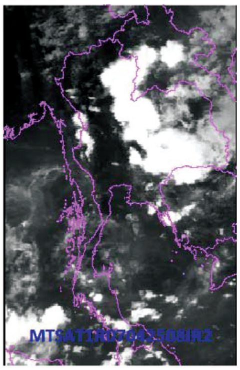

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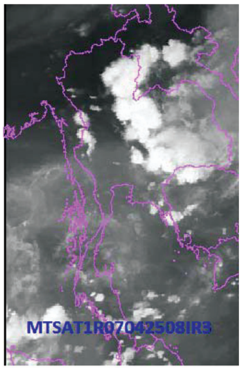

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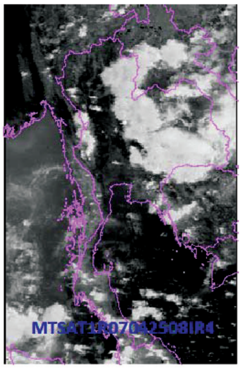
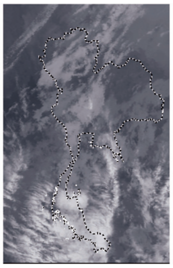


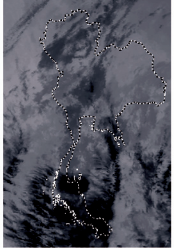
(e)

Figure 3. Examples of the cropped MTSAT-1R satellite image for Thailand portion in (a) visible band (at 0.55-0.90 μm), (b) IR1 band (at 10.3-11.3 μm), (c) IR2 band (at 11.5-12.5 μm), (d) IR3 band (at 6.5-7.0 μm) and (e) IR4 band (at 3.5-4.0 μm)



Row	1	2	3	4	5	6	7	8
0	118	120	121	121	121	120	121	119
1	119	121	121	121	120	119	119	120
2	120	120	121	120	119	119	118	120
3	119	121	121	121	119	119	119	119
4	119	120	120	120	119	120	120	120
5	120	120	121	120	120	120	121	121
6	119	120	120	120	120	121	119	119
7	118	118	119	120	121	121	121	120
8	117	119	120	121	121	122	121	120
9	120	121	121	120	121	122	122	122
10	120	120	121	120	122	122	122	122
11	120	119	120	120	121	121	121	121
12	120	120	120	121	120	120	120	121
13	120	120	121	121	121	121	121	122
14	121	121	121	121	121	121	122	122

(a)



Row	1	2	3	4	5	6
0	286.625	285.735	285.286	285.286	285.286	285.735
1	286.184	285.286	285.286	285.286	285.735	286.184
2	285.735	285.735	285.286	285.735	286.184	286.184
3	286.184	285.286	285.286	285.286	286.184	286.184
4	286.184	285.735	285.735	285.735	286.184	285.735
5	285.735	285.735	285.286	285.735	285.735	285.735
6	286.184	285.735	285.735	285.735	285.735	285.286
7	286.625	286.625	286.184	285.735	285.286	285.286
8	287.065	286.184	285.735	285.286	285.286	284.837
9	285.735	285.286	285.286	285.735	285.286	284.837
10	285.735	285.735	285.286	285.735	284.837	284.837
11	285.735	286.184	285.735	285.735	285.286	285.286
12	285.735	285.735	285.735	285.286	285.735	285.735
13	285.735	285.735	285.286	285.286	285.286	285.286
14	285.286	285.286	285.286	285.286	285.286	285.286

(b)

Figure 4. Examples of the MTSAT TIR image (a) before conversion-displayed as radiance image and (b) after conversion-displayed as equivalent BT image (in Kevin unit)

$$B_i\,(T_b) = 2hc^2V_i^3\;/\;exp\;\{hcv_i/\,k\,(a_{1i}+a_{2i}T_b)\;-\;1\} \qquad (1)$$

where
- B_i : sensor Planck function of channel $_i$
- T_b : brightness temperature
- V_i : central wave number of channel $_i$
- a_{1i} , a_{2i} : band correction coefficients of channel $_i$
- h : Planck constant
- k : Boltzmann constant
- c : speed of light

Values of the constants a_1 and a_2 for each band of MTSAT-1R are given in Table 2.

In this context, the brightness temperature T_b is the equivalent temperature at the surface of the objects under observation (along the field of view (FOV) line of sight) from which the measured radiance was first released.

To assist the automatic conversion from radiance image to corresponding BT image, the conversion module was developed based on the Spatial Modeler Language and ERDAS Macro Language. The module was created for general use with TIR images from any weather satellite

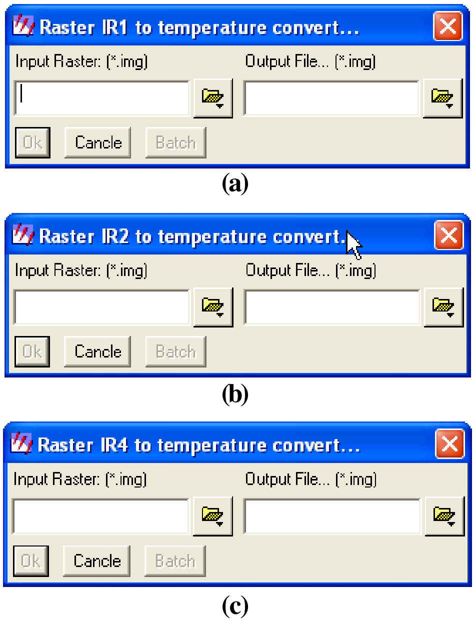


Figure 5. The GUI appearance of the derived radiance/BT conversion module (a) GUI for the conversion of raster IR1 (b) GUI for the conversion of raster IR2 (c) GUI for the conversion of raster IR4

Table 2. Values of the constants a_1 and a_2 for each MTSAT-1R band (MSC, 2009)

Channel	Wave number ν (cm^{-1})	Band correction coefficients a_1	Band correction coefficients a_2
IR1 (10.8 µm)	926.6118	0.3592380	0.9987587
IR2 (12.0 µm)	833.1675	0.1968675	0.9992525
IR3 (6.8 µm)	1482.2068	0.3785336	0.9991187
IR4 (3.8 µm)	2652.9316	2.3473427	0.9969755

Table 3. Example of the conversion table for TIR images of MTSAT-1R

Radiance value	Equivalent brightness temperature (in Kevin unit)			
	IR1	IR2	IR3	IR4
0	329.941500	329.940000	299.967083	319.969643
1	329.625500	329.593333	299.799306	319.862024
2	329.309500	329.246667	299.631528	319.74405
3	328.993500	328.900000	299.463750	319.646786

where the conversion look-up table is available and was added as an extended utility tool in the ERDAS menu. The graphical user interface (GUI) appearance of the module is shown in Figure 5. Note that, in the module, only the conversion of bands IR1, IR2 and IR4 were available for the present study as they were needed in the analysis. However, the application could be implemented conveniently for an IR3 image if required. The input file is the radiance that have a CTT greater than 10°C.

However, by setting a threshold at this value, it can enable the detection of warm clouds that have a CTT between 0 and 10°C and also the mixed cold/warm clouds that may have temperatures between 0 and -20°C. The identifi cation of cloud type on the image was still not done at this stage but, generally, the clouds at temperatures between 10 to -20°C are usually the growing cumulus cloud, or some stratiform clouds, that might be able to produce a shower or light rainfall but not heavy rainfall. But clouds with temperatures less than -40 or -50°C are likely to be rain-bearing clouds like cumulonimbus; however, these also can be cold high clouds like cirrus.

In this work, the brightness temperature data on used cloud images were classified into 8 classes (at intervals of 10°C) as described in Table 4 and some examples of the classified CTT maps are shown in Figure 6.

Cloud Classification Scheme

The final step of the model developing process was to classify the types of clouds that appear on the satellite images (in the form of the CTT map). The ultimate goal was to identify the existing cumulonimbus cloud for further use in the analysis of cloud-rainfall relationship. This could be done using the bi-spectral or split window methods. As visible images are valid only during daytime when the sunlight is still strong while TIR images are available both in daytime and nighttime, therefore the split-window method was chosen over the bi-spectral method in this research. In theory, both methods have the same fundamental principle, which is to establish some proper thresholds and apply them to the images for the classification of the cloud types needed.

In this study, data from bands 1 and 2 of MTSAT-1R were selected for use in the split-window analysis as they are usable both in day time and nighttime. However, at nighttime, the difference between BTs measured in the shortwave (center at 3.75 μm) and longwave (11 μm) IR ($TB_{3.75}$- TB_{11}) can also be used to detect partial cloud or thin cloud within a sensor's FOV. The small or negative differences are observed only for the case where an opaque scene (such as thick cloud or the surface) fills the FOV and negative differences occur at night over extended clouds due to lower cloud emissivity at 3.75 μm channel.

Table 4. The classification scheme of cloud top temperature map

Class	Range (in °C)	Range (in K)	Potential cloud types
1	0 to 10	273 to 283	Warm cloud like cumulus or stratus
2	-10 to 0	263 to 273	(that have only water droplets as main component)
3	-20 to -10	253 to 263	Mixed clouds (that have both water
4	-30 to -20	243 to 253	droplets and ice crystal as main
5	-40 to -30	233 to 243	components)
6	-50 to -40	223 to 233	Huge mixed cloud like
7	-60 to -50	213 to 223	cumulonimbus or cold high clouds (like cirrus or cirrostratus that have
8	< -60	< 213	only ice crystal as main components

Similarly, at nighttime, the 6.7 µm TIR channel can also be employed to identify the thick cumulonimbus cloud. The idea is that low clouds are buried in the water vapor, and since the 6.7 µm channel sees the temperature of the cooler water vapor present above the cloud, the satellite-measured temperature would be lower than the actual CTT. But the same cloud, when observed at 11 µm will yield a temperature much closer to the true CTT. Therefore, the difference between the 2 measurements will be large. Conversely, for high and thick cloud, the values in this case are typically small (Kurino, 1997a, b).

High Cloud Filtering

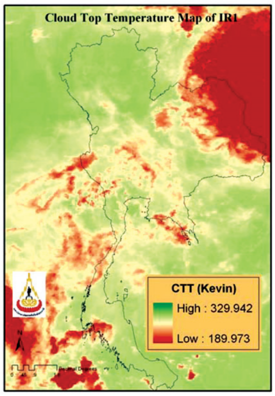
One of the major problems normally found in the identification of cumulonimbus clouds on the satellite images is that their apparent CTT ranges still somewhat overlaps with the high and cold clouds (especially thin cirrus). Therefore, to reduce the confusion in the interpretation of further classification results, the high clouds must be screened off the map beforehand. Here, the threshold index for high cloud identification was set based on the observed difference in values of BT in the IR1 and IR2 bands for those clouds.

In this process, samples of high clouds were distinguished on the cloud map based on their apparent structure in the visible image and the variation in spectral values in the IR1 and visible bands (low in visible and high in IR1). And to assure the validity of the selection more, the images in use were chosen from only in the early morning of winter days on which all other middle/low clouds did not form much. Then, the BT values (cell-based basis) of those chosen samples in the IR1 and IR2 bands were assembled and some basic statistical parameters e.g. mean, range and SD were calculated. The calculation was also performed for $\triangle T$ (T_{11}- T_{12}) and results are given in Table 5 and Figure 7. From the data, thresholds for screening of high clouds (especially thin cirrus) are $T_{11} < 250$ K (-23°C) and $\triangle T > 1.5$ K (upper-bound values of the variation). Applications of these thresholds are shown in Figures 8 and 9.

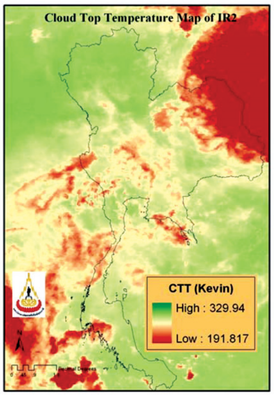
This screening process was also applied to the cumulonimbus cloud to ensure that the screened cirrus clouds (under the aforementioned thresholds) have less or no impact on the existence of actual cumulonimbus cloud on the images. Results of the calculation were illustrated in Table 5 along with the high cloud data. Data in the Table could help us define potential thresholds for the classification of high clouds, middle or low clouds, and cumulonimbus clouds for Thailand; for example, the threshold to separate cumulus from cumulonimbus should be greater than 250 K for infrared 1.

Development of the Classification Model

The main outcome of the necessary classification model is a cloud distribution map on which the potential high clouds are already



(a)



(b)

Figure 6. Examples of the classified CTT map over Thailand based on the MTSAT image of (a) band IR1 and (b) band IR 2 as shown in Figure 3. (Apr 25, 2007 UTC00 images)

filtered off the scene. As a result, only clouds (apart from high clouds) that have a CTT less than 10°C will be identified and presented on the output cloud maps. The classification module was designed to fulfill this objective in which 3 main operating steps were devised:

(1) Input MTSAT-1R image files bands IR1 and IR2,

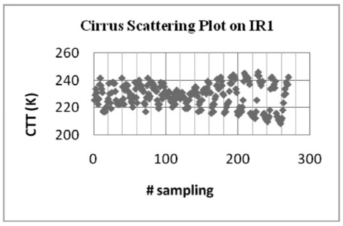
(2) Filter potential high clouds on the input images based on thresholds that are primarily set in the script (T_{11} and $\triangle T = T_{11} - T_{12}$), and

(3) Generate the output cloud map files which are the cirrus map, cirrus-filtered map, and all classified cloud maps (cloud with CTT < 283 K)

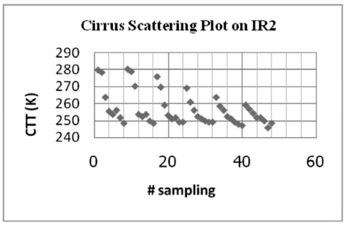
The operation at each step was controlled by the specific source codes written as SML/ EML script and added as a utility tool in ERDAS's Utilities section (see Figure 10 for more detail). Though, the cirrus cloud and warm cloud maps were not needed in the analysis, they are necessary for the study of the Earth's energy budget and weather variation on regional or global scales.

Table 5. BT and △T statistics (in Kevin unit) for the high cloud and cumulonimbus cloud over Thailand (as observed by IR1 and IR2 channels of MTSAT-1R)

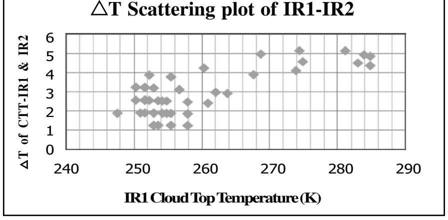
Cloud type	Parameter	Mean	Minimum	Maximum	SD
	IR1 (11 µm)	253.72	222.43	284.83	14.02
High clouds	IR2 (12 µm)	249.89	219.48	280.44	13.03
	△T	3.8	2.95	4.38	0.99
	IR1 (11 µm)	233.73	197.62	84.83	28.23
Cumulonimbus	IR2 (12 µm)	231.39	198.07	280.44	26.15
	△T	2.34	-0.4	74.38	2.07



(a)



(b)



(c)

Figure 7. Scatter plots of IR1/IR2 BT and IR1/DT of high cloud samples

Results

Relationship Between Rainfall and Cloud Properties

In theory, the intensity of rainfall amount depends directly on the type of cloud where most heavy rainfall is from cumulonimbus cloud and light rain normally is from the stratiform cloud. As these clouds naturally locate at different altitudes, their usual CTTs tend to be distinguishable on satellite TIR images where cumulonimbus clouds have a significantly lower CTT as their top surface is situated much higher compared with the stratiform cloud, or other middle or low clouds.

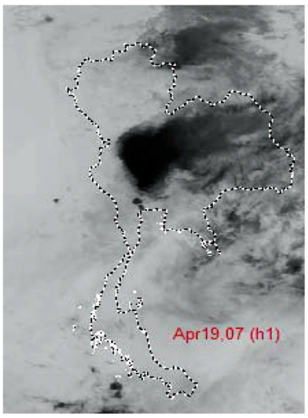
As a result, it is possible to identify the cumulonimbus cloud based on data of CTT and this knowledge can be related to the potential amount of the observed rainfall later on. Also, the amount of potential rain clouds as a whole (not only cumulonimbus) can be linked to rainfall observed each day which is also discussed in detail in this section.

Rainfall Intensity and CTT

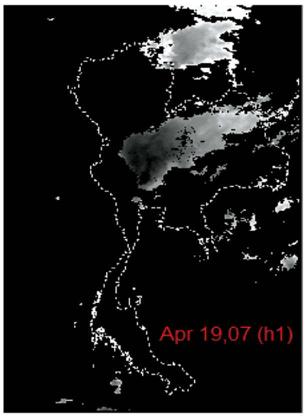
The first study was conducted to examine the general characteristics of the lowest hourly CTT on the MTSAT-1R satellite images used (on the seasonal basis) and the amount of maximum daily rainfall observed in the country that was classified into 5 groups: 0-20, 20-40, 40-60, 60-80, 80-100 and >100 mm. The classes represent days with light rainfall to very heavy rainfall respectively. Also, data of the recorded hail days are displayed as a comparison, as hail can originate from the cumulonimbus cloud only; therefore, on the hail days, there must be cumulonimbus cloud present in the satellite images.

From Figure 11, it can be primarily concluded that the signs of the cold cloud appearance (e.g. clouds with a temperature less than 240 K) are more pronounced in the rainy season than in summer or winter. In addition, for heavier rain days, the less CCT values were normally found especially in summer (where the CTT as low as 175 K could be found). This means some clouds on that day grew much higher than usual.

For the hail days (occurring in summer), the CTTs can become spectacularly low, e.g. < 200 K, in a very short period of time. This could indicate the rapid growth of cumulonimbus cloud (under the unstable air) which is an original source of the hail event found. This is quite in contrast to the formation of cumulonimbus cloud in the winter which takes more time than in summer or the rainy season. And, as seen in Table 6, the minimum CTT for hail in 2006 was 183.05 K and in 2007 was 173.53 K; this means that a hail event might be found on days that have CTT less than about 183 K (about -90°C).



(a)



(b)

Figure 8. Examples of cloud images (a) with and (b) without high cloud appearance, example on Apr 19, 2007 (h1)

Rainfall Estimation using Lowest CTT

The amount of rain rate has long been known to be related to the CTT of the rain clouds where the lower CTT indicates the higher amount of rainfall created. However, based on several previous studies, the pattern of this relationship is still subject to the time period and places of the study. In Thailand, most studies on this issue focused mainly of the cloud/rainfall relationship based on data at some selected stations (normally less than 20 stations). Therefore, in principle, their results still cannot explain the variety of the cloud/rainfall relationship in Thailand as a whole. To gain more knowledge of this relationship in a wider scope, more stations covering a wider area and longer time-span of rain/cloud record are needed, which is significantly fulfilled in this study.

Here, the relationship between cloud/rainfall in Thailand (on a seasonal basis) was investigated based on data of minimum CTT in the specified period and total rainfall amount observed during that period from a number of weather stations across Thailand.

The assumption here is that, the lower the CTT, the higher the amount of rainfall observed. The overall results of the study are shown in Figure 12.

It can be seen in Figure 13 that the relationship between rainfall amount and lowest CTT found in the analysis still did not exhibit a clear pattern where the highest correlation of 0.6277 was seen in the rainy season but in summer and winter the correlation level was still rather low (less than 0.5). This means the CTT value alone cannot be used as the sole indicator of the rainfall amount observed each day. Some other factors, like the type of cloud or the period of being cold cloud should also be taken into consideration.

However, in the rainy season, the CTT was found to be correlated best to the observed rainfall amount and the relation was applied to predict the rainfall amount on 16 August 2007 to test its validity in rainfall prediction. Results of the study are shown in Table 7 where most predicted values were lower than the real observed ones by about 30%.

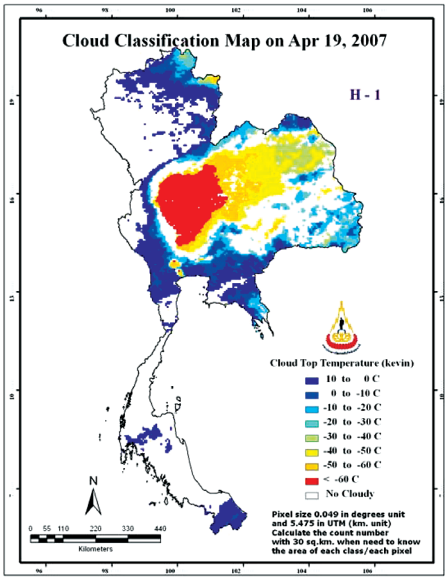


Figure 9. Example of cloud image after the high-cloud filtering process (without high cloud appearance) on April 19, 2007 (h1)

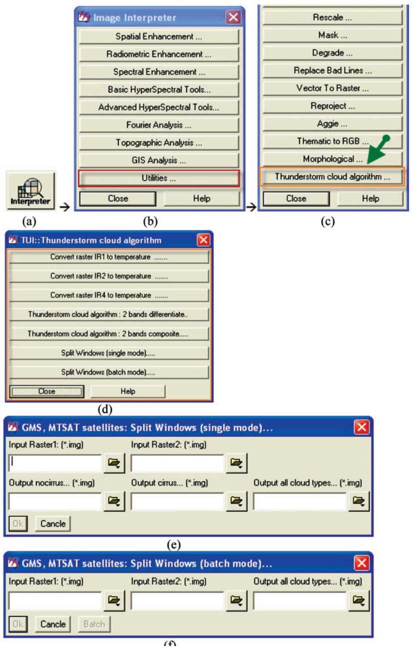


Figure 10. Step-by-step GUI of derive ERDAS module for cloud classification

Rainfall Intensity and Cloud Cover Area

As mentioned earlier, not only the CTT, which is being a crucial indication of the rainfall amount observed each day, but the amount of cloud cover is also another main factor. Here, the relationship between the observed daily rainfall and average amount of cloud cover on each day taken from the satellite images is investigated. To achieve this objective, several cases were examined based on the level of the rainfall intensity and the recorded hail days. Results are shown in Figure 13.

From the results obtained, it is clearly seen that the amount of observed daily rainfall has a high correlation with the amount of cloud cover seen each day, with $r^2 > 0.8$ in all cases especially on the days with heavy rainfall (e.g. > 80 mm). A high correlation was also found for the hail days (with $r^2 = 0.8915$). As the cloud cover here includes all types of cloud seen on the satellite image, this high correlation might

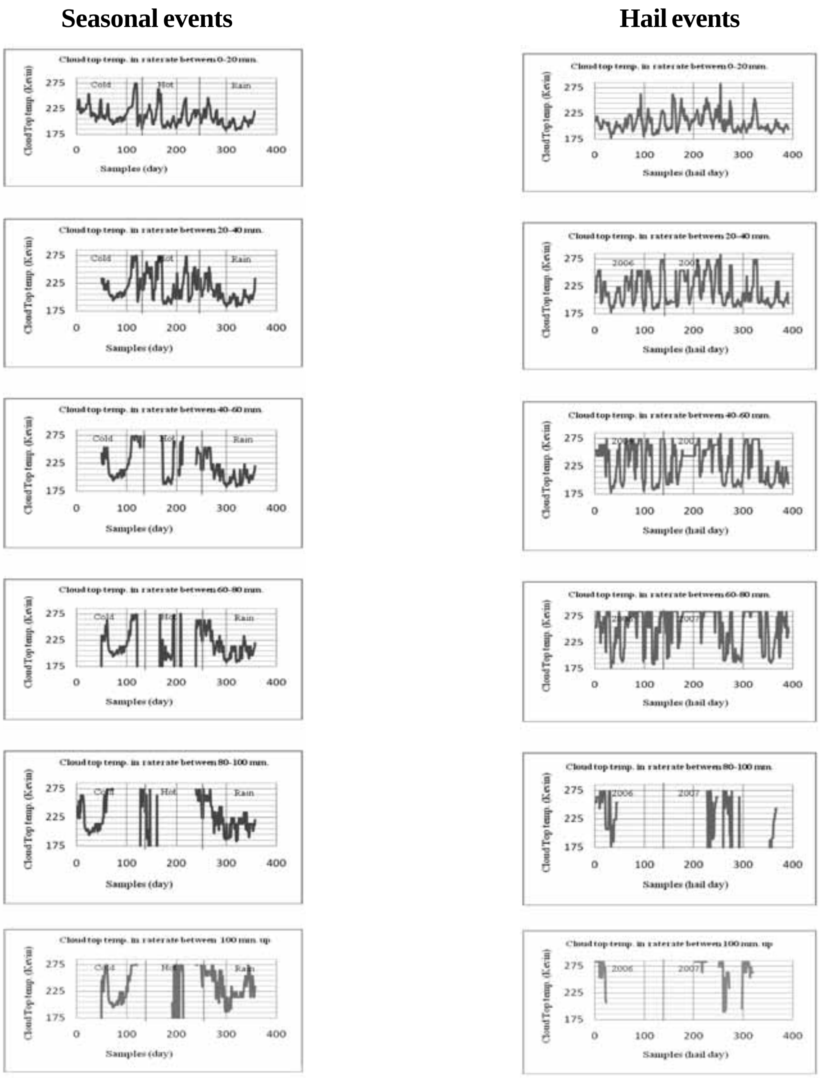


Figure 11. Data of the minimum hourly CCT on the used MTSAT-1R satellite images on different season and also for the chosen "hail" days in 2006 and 2007

indicate that most types of clouds should have a contribution to the rainfall observed each day.

Conclusions and Recommendation

The main objective of this study is to analyze the relationship between rainfall intensity and the associated cloud properties (CTT and cloud cover area) in Thailand based on the selected case studies occurring during years 2006 and 2007. In addition, the classified cloud data was also applied for the study of seasonal cloud and rainfall distribution during those specified years.

To achieve the required tasks, the automatic cloud classification model was developed first based on the observed CTT seen on the TIR image (IR-1 band) of MTSAT-1R satellite. And to reduce the confusion between cold high clouds, like cirrus, and the rain-bearing cumulonimbus cloud, the potential high clouds were filtered off at the beginning of the classification process using the split-window technique in which the threshold temperatures $T_{11} < 250$ K (-23°C) and $\triangle T > 1.5$ K (T_{11}- T_{12}) were employed according to the values being analyzed from the cloud samples. The CTT maps were then generated and all clouds with CTT greater than 10°C were identified on the maps and used to describe the pattern of cloud distribution and to find the relationship with the rainfall amount observed at the same geographical locations.

From the analysis of seasonal cloud and rainfall distribution and knowledge of weather information provided from the responsible agencies, it can be concluded that patterns of seasonal cloud and rainfall distribution in Thailand are the product of the combined effects of several main driving factors. In summer, these are the local convective system, the cold air mass, the monsoon trough, the westerly wind, and the low pressure area from the ocean. In the rainy season, these are the monsoon trough, the southwest monsoon, the tropical cyclone and the low pressure area from the ocean. And in winter, these are the cold air mass (weather front), the northeast monsoon (for the south), and local convection. Most

Table 6. Statistics of the lowest CTT (in Kevin unit) for seasonal and hail events

Statistics	Winter	Summer	Rainy	Hail-06	Hail-07
Minimum	197.60	193.98	185.51	183.05	173.53
Maximum	274.39	281.16	282.09	279.27	282.09
Mean	218.79	222.61	219.73	224.50	217.53
SD	13.87	22.55	20.12	25.38	21.46

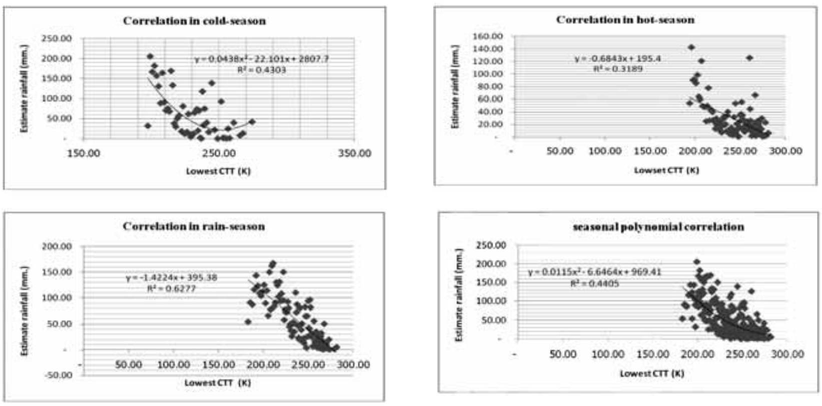


Figure 12. Relationship between rainfall amounts and lowest CTT in different season based on data from several stations across Thailand

observed floods occurred in the rainy season as results of the strong monsoon trough, the southwest monsoon, and the tropical cyclone. But all reported hails were observed in March and April of each year.

In general, less cloud cover was seen in cold time due to the more stable air, especially the rain cloud. In summer, most observed rain clouds were developed and dissipated in a short time period (within a few hours) and CTT can decrease as low as 175 K. These very cold clouds are normally associated with the great cumulonimbus cloud which is the source of the hail event found in summer. During the rainy season, clouds are more visible all day long, especially the cold cloud that can last for a considerable period of time (up to 8-10 h).

The analysis of the proper relationship between daily measured rainfall across the country and the corresponding CTT indicated that the relationships between rainfall amount and observed CTT did not exhibit a clear pattern where the highest correlation of 0.6277 was seen in the rainy season, but in summer and winter, the correlation level was still rather low (less than 0.5). This means the CTT value alone cannot be used as the sole indicator of the rainfall amount observed each day.

In addition, it is clearly seen from the study that the amount of the total daily rainfall has a high correlation with the amount of cloud cover area seen each day, with $r^2 > 0.8$ in all cases especially on the days with heavy rainfall (e.g. > 80 mm) or on the hail days (with $r^2 = 0.8915$). As the cloud cover here includes all types of cloud seen on the satellite image, this high correlation might indicate that most types of clouds, should have a contribution to the rainfall observed each day.

Although some satisfied outcomes have been achieved in this study, especially the automatic cloud classification model for the TIR weather satellite images and the high correlation between cloud cover area and total rainfall amount, there are still many interesting issues that need to be investigated more. For example:

(1) The relationship between CTT and rainfall accumulated in shorter time period, for example, within 3 h or 6 h, and at more specific locations;

(2) The applicability of free data from some other weather satellites, especially TRMM, in the study of the rain and cloud relationship in the country;

(3) The developing pattern of rain clouds

Table 7. Application of the cloud/rainfall relationship (as described in Figure 12) for rainfall prediction on 16 August 2007 (the relation is y = -1.4224x + 395.38)

Lowest CTT (K)	Rainfall amount (mm)		% Error	%Accuracy
	Actual	Predicted		
232.86	50.00	64.16	-35.84	64.16
231.98	26.00	65.41	-34.59	65.41
231.10	36.60	66.67	- 33.33	66.67
230.20	50.00	67.94	- 32.06	67.94
229.29	44.50	69.25	-30.75	69.25
228.36	80.30	70.56	-29.44	70.56
227.43	92.30	71.89	-28.11	71.89
226.46	73.00	73.26	-26.74	73.26
225.49	72.30	74.64	-25.36	74.64
224.50	77.20	76.05	-23.95	76.05
223.50	57.80	77.48	-22.52	77.48
	Average		**-29.34**	**70.66**

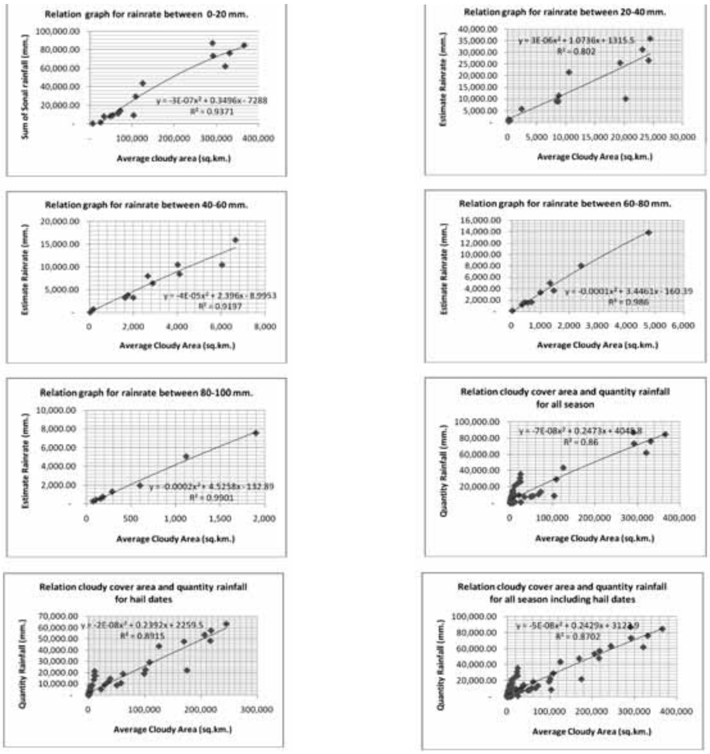


Figure 13. The relationship between average daily cloud cover and the total amount of observed rainfall for different levels of rainfall intensity and the hail days

in different seasons and the relationships between their properties, e.g. size, area cover, CTT, or the period of being cold clouds.

(4) Consideration of some other factors, like type or thickness of cloud body or period of being cold clouds for the analysis of the cloud and rain relationship.

(5) The relationship between CTT and rainfall accumulated in other weather satellites or on MTSAT-1R on other infrared bands

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