Observation and numerical experiments of orographic precipitation in the Mae Chaem watershed in Southeast Asia

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Abstract

A dense tipping-bucket rain gauge network was established in the Mae Chaem watershed in the mountains of northwestern Thailand as part of the Global Energy and Water Cycle Experiment (GEWEX) Asian Monsoon Experiment-Tropics (GAME-T). Investigations of rainfall amounts, intensities, durations, and frequencies in the rainy season revealed strong orographic rainfall enhancement in the region. The larger amount of high-altitude rainfall was attributed to duration and frequency rather than intensity. By investigating orographic precipitation using a regional atmospheric model, the duration and frequency of rainfall at high altitudes were found to be caused by two mechanisms: 1) convective clouds over mountains activate in the evening, and 2) seeder-feeder mechanism caused by strati formed by radiative cooling or heating in the middle troposphere and orographically triggered low-level convective clouds. The results of the numerical simulations were quite consistent with the measurements acquired from the tipping-bucket rainfall gauges.

Keyword: Orographic Precipitation, Regional Atmospheric Model, Tropical Mountainous region, Southeast Asia.

1. Introduction

Many researchers have examined temporal and spatial precipitation distributions. These studies are important for water resource and flood control management, and for designing and planning various engineering projects (Smith, 1992; Palmer and Rälsänen, 2002). Precipitation generally increases with elevation, and mountain ranges can create leeward-side “rain shadows”. This implies some underlying mechanisms which play an important role in organizing precipitation systems in a mountainous region. However, worldwide, only an irregular, coarse grid of precipitation measurement data exists and it is not sufficient to say that mechanisms are fully understood.

Only about 6,600 stations worldwide archive rain gauge data through the Global Telecommunications Network or other regional or national data collection centers (Rudolf et al., 1994). Both precipitation data and data archives are also mostly located in mid- or high-latitude developed countries. Consequently, most studies, however, have focused on mid-latitude developed countries, which are more likely to have the necessary high temporal resolution rainfall records. In recent years, hydro meteorological networks are installed in some ungauged high elevation basins. Tropical countries typically have sparse operational rain gauge networks and extremely limited high temporal resolution (one hour or less) precipitation records.

Point-to-area and gauge gaps are the biggest problems for gauge analysis. Huffman et al. (1995) noted that rain gauge analysis at the Global Precipitation Climatology Centre (GPCC; Rudolf et al., 1994) revealed important quantitative differences from GPCP satellite estimates, particularly in Southeast Asia and Central America. Xie and Arkin (1997) also noted large biases and random errors in a GPCC gauge, positioned in an area of Thailand affected by significant mountain-induced precipitation variations.

This paper investigates rainfall frequency, amount, intensity, and duration on an event basis in the Mae Chaem watershed, a tropical mountainous region using high temporal resolution tipping-bucket rain gauge data and a state-of-the-art regional atmospheric model to understand the statistical precipitation structures in the rainy season that induce significant bias and spatial sampling error. The sections that follow describe the study area, dataset, methodology, and results.

2. Study Area, dataset, and relationships among the quantity, intensity, duration, and frequency of rainfall

Since 1998, Global Energy and Water Cycle Experiment (GEWEX), Asian Monsoon Experiment-Tropics (GAME-Tropics) researchers have conducted high temporal resolution ground-based rainfall observations in mountainous areas of Thailand. Fifteen tipping-bucket type rain gauges with sub-hourly (one minute) time resolutions were installed at sites 380 to 2496 m above sea level in the Mae Chaem watershed (Fig.1). The watershed covers an area of 3853 km^2 (Dairaku et al., 2000, 2004; Kuraji et al., 2001).

The Mae Chaem watershed is located in the northwest Chao Phraya River basin. The highest peak in the watershed, Doi Inthanon, rises 2,535 m above sea level. Data logger records the time by the second when 0.5mm rainfall quantity is observed. Rainfall records used in this study were obtained from 12 sites from 1 June to 31 October, 1998 and from 13 sites from 1 June to 31 October, 1999 in order to investigate the relationships among the quantity, intensity, duration, and frequency of rainfall during the rainy season.

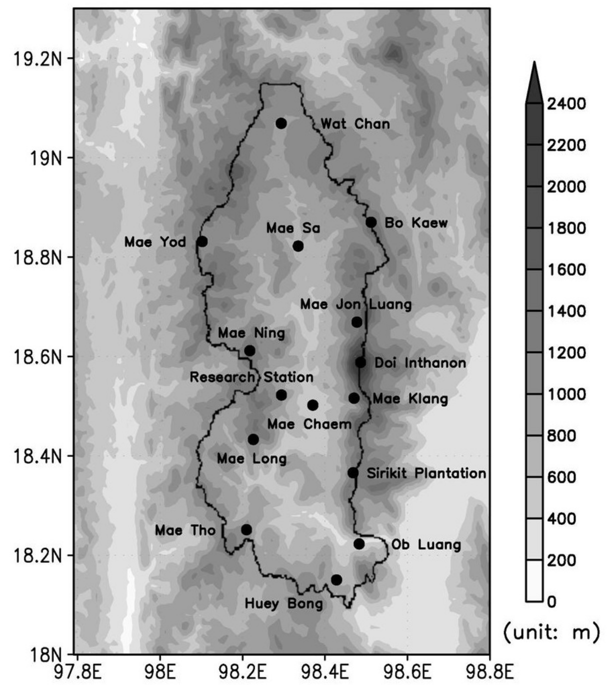

Fig. 1: GAME-T rainfall observation stations in the Mae Chaem watershed, Thailand.

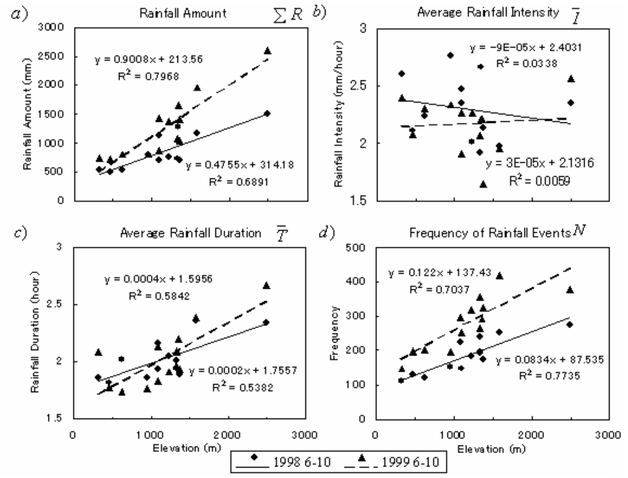

Fig. 2: Relationships between elevation and (a) rainfall amount, (b) average rainfall intensity, (c) average rainfall duration, and (d) frequency in 1998 and 1999. In this legend, “6-10” denotes the months June-October.

As shown in Figure 2a, there was a significant regional variation in the rainfall recorded by the rain gages. Since the final quality of merged analysis is primarily determined by the quality of input data sources, improving the quantitative estimation and the individual data sources is essential. It is clear that the quantity of rainfall varies with elevation in this watershed throughout the rainy season and the inter-annual variation in the quantity of rainfall is quite large. As shown in Figure 2b, the average intensity of the rainfall is not correlated with the elevation. In other words, the higher quantity of rainfall at higher elevation stations, shown in Figure 2a, is not attributed to the higher intensity of rainfall. The average duration of the rainfall increases with the elevation in Figure 2c. As shown in Figure 2d, the number of rainfall events also depends on the elevation. In other words, increased duration and higher frequency contribute to orographic rainfall.

Regardless of the large differences in the quantity of rainfall between 1998 and 1999, the orographic characteristics of rainfall, which are attributed to higher duration and frequency rather than to intensity, are common to both 1998 and 1999.

3. Model and Experiments

As described in the section 2, the rainfall characteristics in the watershed are strongly influenced by the topography. For effective management and planning of water resources in such a region, it is necessary to investigate the influences of mountains on rainfall characteristics and processes.

Two-dimensional numerical experiments were conducted. A Regional Atmospheric Modeling System (RAMS) developed by Colorado State University was used in this study (Pielke et al., 1992). A two-dimentional, nonhydrostatic compressible dynamic-equations model was configured in the present study. A liquid- and solid-phase bulk microphysics parameterization is used to simulate cloud activity. The two-stream radiation scheme (Harrington et al., 1999) is used as a radiation parameterization. LEAF-2 (Walko et al., 2000) is used as a soil and vegetation model. Topography data with a 30” longitude resolution (GTOPO30) is used and incorporated in this simulation. Land-use data that is estimated from satellite data (AVHRR) by USGS is incorporated. The sea surface temperature was set at the monthly climatological average for July. Because of two-dimensional simulations, the Coriolis force is excluded.

We used two interacting nested grids. The 1st horizontal domain (east-west direction) is 1,680 km wide and is represented by 420 grids with 4km grid spacing. The 2nd horizontal domain is 401.6 km wide with 502 grid points of 800 m horizontal resolution and is nested within the 1st domain to take synoptic features into account. On the other hand, the vertical grid setting is identical between the two grids. The vertical grid is a terrain-following σ_z coordinate, and the gird space is stretched from 30 m to 500 m maximum. The vertical grid points are set to 60 (approximate 22.3 km above sea level). The solid line in Figure 3 shows the specified 1st simulation domain with the coarse grid interval. The thick solid line indicates the nested 2nd simulation domain with the fine grid interval.

As an initial condition, thermodynamic and wind conditions are averaged in the area of 1.5°×1° (17.75N-19.25N, 97.75E-98.75E, solid rectangle shown in Fig. 3) over the watershed (dashed rectangle shown in Fig. 3) for the period of three months from June to August using the GAME-reanalysis data (Yamazaki et al., 2001). The averaged vertical profile of the initial condition indicates a moist condition in the lower troposphere, westerly winds in the lower troposphere and easterly winds in the upper troposphere. The lifted condensation level of the thermodynamic condition is 877.2hPa. The low saturation level implies that clouds tend to be formed by a dynamic orographic upward motion (Fig. 4).

A numerical experiment incorporating the averaged condition as the initial condition and several sensitivity experiments were conducted. Each experiment was integrated for 5days. The first day of the experiments were excluded as a spin-up period that is required for sufficiently adjusting the initial condition to the complex terrain in the simulation grids. Precipitation tends to be triggered and that enhanced in mountainous regions and precipitation systems move eastward.

As shown in Figs. 5, accumulated surface precipitation for four days excluding the 1st day of the experiment over the watershed in the nested grid shows the enhancement of the precipitation according to the terrain. The rainfall duration of the accumulated precipitation for four days over the watershed in the nested grid tends to be greater at higher altitudes and the average intensity of the rainfall does not seem to be correlated with the topography. The results are obtained from the two-dimensional numerical simulation for 5 days. These simulation results cannot be compared directly to the results of the statistical analysis using data from rain-gage observations for a 5-month period in 1998 and 1999; however, the results of the simulation are quite consistent with the fact that a larger quantity of rainfall recorded at a higher altitude can be attributed to a greater duration and higher frequency rather than to a greater intensity of rainfall.

In this numerical experiment, mainly two mechanisms were observed. First, if there are no clouds above the ground, convective clouds are triggered at mountainous regions in the evening in unstable atmospheric conditions that occur as the result of the ground heating due to strong insolation. Then, due to the hydraulic jump (Durran, 1986) and upslope wind produced by thermal local circulation, the clouds are organized into squall lines and propagate eastward. This mechanism is identical with the recent research (Satomura, 2000).

Second, a seeder-feeder mechanism (Smith, 1977) was observed. At night, some of the decaying convective clouds triggered in the evening were reorganized into stratus clouds around 5 or 6 km above sea level due to the radiative cooling at the top of the clouds. In addition, convective clouds around 2 or 3 km above sea level occur in the pure orographic flow produced by westerly moist monsoon wind in the lower troposphere and complex terrain. In this two-layer cloud structure, convective clouds were triggered from the stratus clouds aloft by radiative cooling during the night or by radiative heating during the day. These convective clouds produced precipitation that was locally enhanced by low-level convective clouds over the mountains. Because the low-level cloud base was around 2 km, clouds tended to frequently occur and stay over the mountainous regions around 2 km above sea level. The clouds on both layers moved eastward in association with the westerly moist monsoon wind in the lower troposphere. When the sky cleared, the convective clouds were activated again in the mountainous regions.

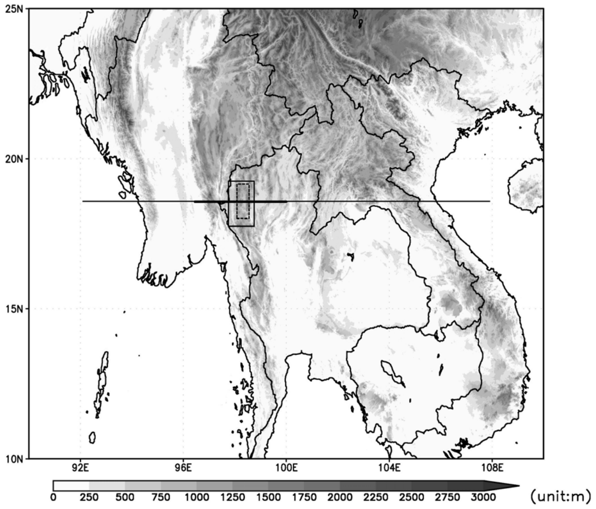

Fig. 3: The solid line indicates the numerical simulation domain. The thick solid line indicates the nested simulation domain. The solid rectangle shows the area used for calculating an initial condition for the numerical simulation from GAME-reanalysis data. The dashed rectangle corresponds to Mae Chaem watershed.

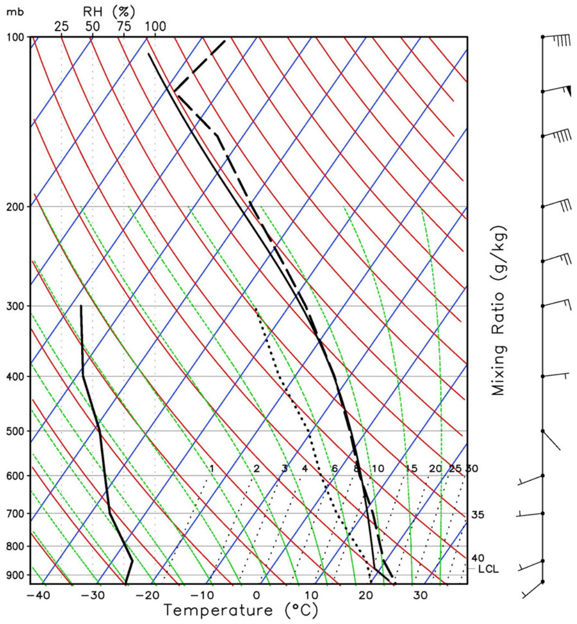

Fig. 4: Initial condition for the numerical simulation calculated from GAME-reanalysis data. The broken line indicates the temperature. The dotted line indicates the dew-point temperature. The solid line on the right shows the surface parcel trace. The solid line on the left shows the relative humidity

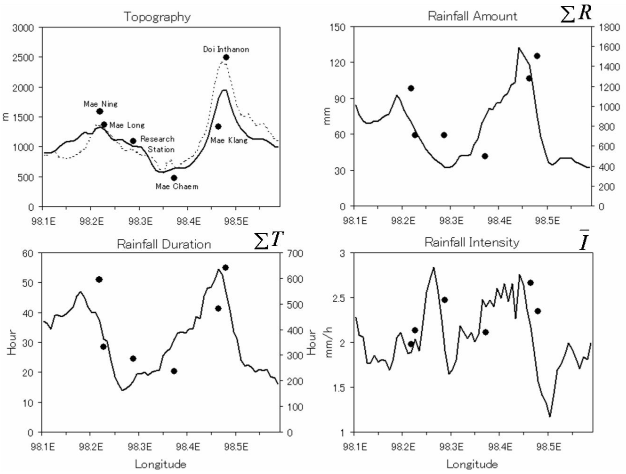

Fig. 5: Comparison of simulated results (solid lines) to the observations (circles) over the watershed. Topography used in the model and the elevation of the stations (Upper left). Accumulated surface precipitation of simulation for 4 days over the watershed in the 2nd domain and observed surface precipitation for 5 months, June-October (Upper right). Average rainfall duration of simulation and observations (lower left). Average rainfall intensity of simulation and observations (lower right).

4. Conclusions

The conclusions are as follows:

1) Rainfall quantity varies significantly according to elevation in this watershed throughout the rainy season. The fact that a larger quantity of rainfall is recorded at higher altitudes is attributed to greater duration and higher frequency rather than to higher intensity of rainfall.

2) In the numerical experiment, greater rainfall duration and higher frequency at high altitude are caused by two mechanisms; 1) convective clouds are activated by mountains in the evening, and 2) stratus clouds formed by radiative cooling at the top of clouds and low-level orographically triggered convective clouds cause a seeder-feeder mechanism.

Acknowledgements

This study was conducted as a GEWEX/GAME activity supported by a grant No.11201202 (representative: Prof. Katumi Musiake) and Grant-in-Aid for JSPS Fellows from The Ministry of Education, Science, Sports, and Culture, Japan. It was directed by one of the GAME-Tropics sub-committees. Rainfall observation field works in the Mae Chaem watershed was conducted by Prof. Suzuki and Dr. Kuraji and in cooperation with the Royal Forest Department and Kasetsart University, Thailand. The authors gratefully acknowledge the helpful arrangement of GAME-T observation data by Dr.Yasushi Agata and the helpful discussions with Prof. Takehiko Satomura, Prof. Jun Matsumoto, Mr. Thada Sukhapunnaphan.

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