Rainfall Amount, Intensity, Duration, and Frequency Relationships in the Mae Chaem Watershed in Southeast Asia

KOJI DAIKAKU
Atmospheric Environment Division, National Institute for Environmental Studies, Tsukuba, Ibaraki, Japan

SEITA EMORI*
Frontier Research System for Global Change, Yokohama, Japan

TAIKAN OKI
Institute of Industrial Science, the University of Tokyo, Tokyo, Japan

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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. Despite large rainfall variations, similar patterns were found in the two study years, 1998 and 1999.

1. Introduction

Hydrological changes and the impact of those changes constitute a fundamental global-warming-related concern (Vörösmarty et al. 2000). Faced with threats to human life and natural ecosystems, such as droughts, floods, and soil erosion, water resource planners must, increasingly, make future risk assessments (Schnur 2002). Historically, stable climatic conditions have been assumed for water resource management, planning, and civil engineering designs. However, global climate change may lead to changes in rainfall events (Palmer and Rälsänen 2002). We must learn, therefore, to adapt to climate changes and cope with climate variability (Zwiers 2002). Hydrological predictions that account for global climate change mainly use general circulation models (GCMs) (e.g., Coe 2000; Koster et al. 2000; Vörösmarty et al. 2000; Palmer and Rälsänen 2002; Milly et al. 2002). However, coarse spatial resolutions and uncertain physical processes limit the amount of regional-scale estimates available to planners.

Many researchers have examined temporal and spatial precipitation distributions, especially the distribution of extreme precipitation values. 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 that 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. Researchers have attempted to develop a number of geostatistical interpolation methods to obtain reliable rainfall and rainfall-risk maps in mountainous regions with sparse precipitation measurement coverage (Phillips et al. 1992; Yamada et al. 1995; Weisse and Bois 2001; Kyriakidis et al. 2001). Other researchers have investigated orographic-induced meteorological mechanisms and statistical orographic rain structures (Smith 1986; Stow et al. 1991; Wratt et al. 1996; Barros and Kuligowski 1998; Purdy et al. 2001; Miniscoux et al. 2001; Neiman et al. 2002). Only about 6600 stations worldwide archive rain gauge data through

*Current affiliation: Atmospheric Environment Division, National Institute for Environmental Studies, Tsukuba, Ibaraki, Japan.

Corresponding author address: Dr. Koji Dairaku, Atmospheric Environment Division, National Institute for Environmental Studies, 16-2 Onogawa Tsukuba Ibaraki 305-0053, Japan. E-mail: dairaku.koji@nies.go.jp

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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, have focused on mid-latitude developed countries, which are more likely to have the necessary high-temporal-resolution rainfall records. In recent years, hydrometeorological networks have been installed in some ungauged high-elevation basins. However, only a few studies (Ramage 1964; Thauvin and Lebel 1991; Oki and Musiake 1994; Ueno et al. 1994, 2001; Shuin et al. 1996; Barros et al. 2000, 2003; Lang and Barros 2002, Barros and Lang 2003) have examined rainfall characteristics in a tropical region. Tropical countries typically have sparse operational rain gauge networks and extremely limited high-temporal-resolution (1 h or less) precipitation records.

Rain gauges provide relatively accurate point measurements of precipitation, although rain gauge observations do suffer from systematic errors and biases as caused by wind-induced undercatch, wetting, and evaporation loss (Neff 1977; Golubev et al. 1992; Yang et al. 1998). Point-to-area and gauge gaps are the biggest problems for gauge analysis. Researchers have used infrared and microwave radiance satellite observations to retrieve precipitation information from many parts of the globe. However, estimates made from satellite observations contain nonnegligible random errors and biases due to the indirect relationship between observations and precipitation, inadequate sampling, and algorithmic imperfections (Xie and Arkin 1997). 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.

Understanding rainfall variability within regions is indispensable for applying global climate research results to regional climate and water cycles. As Dettinger and Díaz (2000) noted, relatively high-altitude catchments feed river basins, but weather stations are located at lower altitudes, leading to a low-altitude bias in precipitation estimates for most river basins. Oki (2001) also noted that if a climate model produces weaker and more continuous rainfall intensity than occurs in reality, evapotranspiration from intercepted water values should also increase, resulting in exaggeratedly low soil moisture and runoff values. Direct runoff calculated by land surface models (LSMs) could also appear lower because of the weaker rain rates.

Shuin et al. (1996) studied temporal and spatial rainfall at five ground rainfall stations in order to geostatistically interpolate rainfall and link spatial rainfall data to a radar rain gauge on Indonesia’s Mount Merapi. They compared the rainfall characteristics with characteristics from Mount Fuji in Japan. The study revealed clear diurnal and seasonal precipitation variations on Mount Merapi. The small spatial and temporal rainfall scales were mainly associated with convective rains. Ueno et al. (1994) investigated diurnal variation of rainfall amounts, intensity, and frequency using tipping-bucket rain gauges at four stations located on the Thanggula Mountain range in the central Tibetan Plateau. The results showed insignificant diurnal variations in rainfall amount, intensity, and frequency. Using newly installed rain gauges for a 4-month study, Barros et al. (2000) investigated rainfall characteristics of the 1999 monsoon in the complex orography of central Nepal. Their research revealed higher intensity rains over shorter durations at the lower-elevation stations.

Since 1998, Global Energy and Water Cycle Experiment (GEWEX) Asian Monsoon Experiment-Tropics (GAME-T) researchers have conducted high-temporal-resolution ground-based rainfall observations in mountainous areas of Thailand (Fig. 1). Fifteen tipping-bucket-type rain gauges with subhourly (1 min) time resolutions were installed at sites 380–2565 m above sea level in the Mae Chaem watershed (Fig. 2). The watershed covers an area of 3853 km² (Dairaku et al. 2000; Kuraji et al. 2001). Research revealed that altitude-related rainfall enhancement in the Mae Chaem watershed correlated to the total duration of rainfall and was independent of the mean rainfall intensity (Dairaku et al. 2000). Kuraji et al. (2001) further investigated rainfall spatial scales, mean rainfall intensity, and total rainfall duration in the wet and dry seasons.

Previous studies, however, have not examined the characteristics of individual rainfall events. That is, while studies have investigated average or total rainfall characteristics such as mean rainfall intensities and total rainfall durations, they have not investigated rainfall frequency, amount, intensity, and duration on an event basis. This paper investigates these relationships in the Mae Chaem watershed, a tropical mountainous region using high-temporal-resolution tipping-bucket rain gauge data 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. Methods

a. Study area and dataset

The Mae Chaem watershed study area is one of the GAME-T research sites (Dairaku et al. 2000; Kuraji et al. 2001). Located in the northwest Chao Phraya River basin, the Mae Chaem watershed has an area of 3853 km² (Fig. 1). The highest peak in the watershed, Doi Intanion, rises 2535 m above sea level. Tipping-bucket-type rain gauges (20-cm orifice diameter; 0.5 mm precipitation per tip) with 1-s resolutions have collected rainfall data in the mountainous area since November
1997 (Fig. 2). The observation network consisted of only seven stations before June 1998 but was increased to its present status after that time. Table 1 shows the locations of Mae Chaem watershed rain gauges at elevations ranging from 326 to 2496 m. The watershed’s average altitude is 948 m.

Wind-induced undercatch, wetting, and evaporation losses can cause systematic errors and biases in rain gauge observations (Neff 1977; Golubev et al. 1992; Yang et al. 1998). Wetting loss is evaporation from the inner-wall surface of the rain gauge. Evaporation loss is defined as the undermeasurement of water lost by evaporation before observation. Wind-induced undercatch errors are extremely significant, especially for solid precipitation like snowfall, but in the GAME-T experimental watershed, solid precipitation is rarely observed. It has been reported that for liquid rain, undercatch error using an unshielded rain gauge is only about 4%, and wetting error and evaporation are negligible (Golubev et al. 1992). Thus, error correction was not applied to the rainfall records in this study.

To investigate the precipitation characteristics in the rainy season, the 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 that had complete data. The data collection dates allowed for investigation of rainy-season rainfall amount, intensity, duration, and frequency relationships. Because of incomplete measurements during the study period, 1998 data from the Mae Jon Luang, Mae Tho, and Huay Bong sites and 1999 data from the Mae Tho and Huay Bong sites were not used in this study.

Table 1. Location and elevation of rain gauges in Fig. 2.

<table>
<thead>
<tr>
<th>Station name</th>
<th>Lat (N)</th>
<th>Lon (E)</th>
<th>Elev (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wat Chan</td>
<td>19°04'09&quot;</td>
<td>98°17'37&quot;</td>
<td>955</td>
</tr>
<tr>
<td>Bo Kaeo</td>
<td>18°52'12&quot;</td>
<td>98°30'42&quot;</td>
<td>1330</td>
</tr>
<tr>
<td>Mae Yod</td>
<td>18°49'53&quot;</td>
<td>98°06'07&quot;</td>
<td>1091</td>
</tr>
<tr>
<td>Mae Sa</td>
<td>18°49'20&quot;</td>
<td>98°20'06&quot;</td>
<td>627</td>
</tr>
<tr>
<td>Mae Jon Luang*</td>
<td>18°40'09&quot;</td>
<td>98°28'38&quot;</td>
<td>1356</td>
</tr>
<tr>
<td>Doi Inthanon</td>
<td>18°35'17&quot;</td>
<td>98°29'11&quot;</td>
<td>2406</td>
</tr>
<tr>
<td>Mae Klang</td>
<td>18°30'58&quot;</td>
<td>98°28'13&quot;</td>
<td>1339</td>
</tr>
<tr>
<td>Mae Chaem</td>
<td>18°30'07&quot;</td>
<td>98°22'13&quot;</td>
<td>471</td>
</tr>
<tr>
<td>Research Station</td>
<td>18°31'20&quot;</td>
<td>98°17'40&quot;</td>
<td>1094</td>
</tr>
<tr>
<td>Sirikit Plantation</td>
<td>18°21'57&quot;</td>
<td>98°28'05&quot;</td>
<td>1225</td>
</tr>
<tr>
<td>Mae Ning</td>
<td>18°36'41&quot;</td>
<td>98°13'03&quot;</td>
<td>1585</td>
</tr>
<tr>
<td>Mae Long</td>
<td>18°25'58&quot;</td>
<td>98°13'34&quot;</td>
<td>1369</td>
</tr>
<tr>
<td>Ob Luang</td>
<td>18°13'21&quot;</td>
<td>98°28'58&quot;</td>
<td>326</td>
</tr>
<tr>
<td>Huay Bong**</td>
<td>18°09'01&quot;</td>
<td>98°25'40&quot;</td>
<td>792</td>
</tr>
<tr>
<td>Mae Tho**</td>
<td>18°15'04&quot;</td>
<td>98°12'34&quot;</td>
<td>1220</td>
</tr>
</tbody>
</table>

* Unused station in 1998.
b. Climate factors that describe rainfall characteristics

In previous studies (Dairaku et al. 2000; Kuraji et al. 2001), only two factors, average rainfall intensity and total rainfall duration, were considered in the examination of orographic rainfall characteristics in the Mae Chaem watershed. In order to investigate rainfall amount, intensity, duration, and frequency relationships, the duration of each rainfall event should first be defined using the interval-time method or the mean-time method described by Dairaku et al. (2000).

This study used the mean-time method to define a rainfall event and its rainfall duration and to judge whether a recorded rainfall tipping time met the mean time. As shown in Fig. 3, \( t_n \) \((t_1, t_2, t_3, \ldots)\) represents the tipping time recorded by a tipping-bucket rain gauge, \( T_m \) represents the mean time, and \( T_1 \) represents the starting time of the calculation:

\[
T_1 + T_m(k - 1) \leq t_n < T_1 + T_m k \quad (k \geq 1).
\]

(1)

By this definition, if \( t_n \) satisfies the condition (1), when \( k \) is a certain value, rain will fall continually during the \( T_m \). This study uses 1 h as the mean time (\( T_m \)).

For each rainfall event, the rainfall amount, intensity, and duration relationship is defined as

\[
R_i = I_i T_i,
\]

(2)

where \( R_i \) (millimeters) represents the rainfall amount, \( I_i \) represents rainfall intensity (millimeters per hour), and \( T_i \) represents the rainfall duration (hour) of each rainfall
event \( i \). The total rainfall amount from 1 June through 31 October 1998 and 1999 is represented by

\[ \sum R_i = \sum IT_i, \]

and mean rainfall intensity is represented by

\[ \bar{I} = \frac{\sum R_i}{\sum T_i} = \frac{\sum IT_i}{\sum T_i}. \]

Here, \( \sum T_i \) is the total rainfall duration. Average rainfall duration is defined by

\[ \bar{\tau} = \frac{1}{N} \sum T_i, \]

where \( N \) represents the number (or frequency) of rainfall events.

c. Rainfall amount, intensity, duration, and frequency relationships

Using the above definitions, the total rainfall amount was divided into three factors: average rainfall intensity, average rainfall duration, and frequency. The resultant equation is as follows:

\[ \sum R_i = \sum IT_i = \frac{\sum IT_i}{\sum T_i} \sum T_i = \frac{\sum IT_i}{\sum T_i} N = ITN. \]

This equation introduces average rainfall duration and frequency by defining each rainfall event. This allows us to analyze rainfall amount, intensity, duration, and frequency relationships.

3. Results and discussion

a. Relating rainfall amount, intensity, duration, and frequency to elevation in the Mae Chaem watershed

Figure 4 shows altitude-related orographic rainfall characteristics in the watershed from June to October 1998 and 1999. Equation (6) defines the four variables. Figure 4a clearly reveals varying rainfall amounts by elevation throughout the rainy season and large inter-annual rainfall amount variations. As illustrated in Fig. 4b, average rainfall intensity did not correlate to elevation. In other words, the high rainfall at high elevation stations shown in Fig. 4a was not attributed to high
rainfall intensities. Figure 4c shows that average rainfall durations increased with elevation, while Fig. 4d shows that rainfall frequencies also depended on elevation. In other words, orographic factors contributed to longer rainfall durations and higher rainfall frequencies.

Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP; Xie and Arkin 1997), the Global Precipitation Climatology Project (GPCP; Huffman et al. 1997), GPCC (Rudolf et al. 1994), and the Tropical Rainfall Measuring Mission (TRMM) product 3B43 (Adler et al. 2000) datasets were averaged over the 2° by 1.5° area located at 17.5°–19.5°N by 97.5°–99°E, which corresponds to the Mae Chaem watershed. Though the area (2° by 1.5°) is larger than the gauge area, the differences between the values averaged over 2° by 1.5° area and the values averaged just over the Mae Chaem watershed are very small because of the very coarse grid of global datasets. Average precipitation was estimated for the GAME-T gauge array by taking the average elevation value (948 m) within the watershed boundary (Fig. 2) on the linear regression in Fig. 4a.

Figure 5 shows interannual variations in precipitation amounts from June to October of 1979–99 for all available years from each dataset. All datasets agreed that 1998 was relatively dry, as compared to previous years, while in 1999 all the global precipitation datasets indicated close-to-average rainfall amounts. However, the GAME-T rain gauges placed 1999 rainfall far above the average of global datasets. The accurate estimation of an areal representative precipitation and quality evaluations among datasets are questions beyond the scope of this paper.

A relatively strong dry anomaly in 1998 annual precipitation was found to prevail in most of Southeast Asia by using the CMAP dataset. A wet anomaly was seen in 1999 in the area, though the precipitation around the watershed was close to the normal (not shown). During the period 1997–2000, the global climate system experienced a transition from a strong warm event (El Niño) of the ENSO cycle in sea surface temperature in 1997/98 to a strong cold event (La Niña) in 1999/2000 (Anyamba et al. 2002). However, the influence of the global circulation associated with ENSO on the mesoscale rainfall characteristics in our study region is not identified clearly.

In summary, all datasets showed 1998 as a relatively dry year and found large rainfall amount variations between 1998 and 1999. Orographic rainfall characteristics attributed to higher rainfall duration and frequency rather than to rainfall intensity were also common in both 1998 and 1999.

b. Rainfall events that contribute to orographic rainfall

To investigate the rainfall characteristics indicated in Fig. 4 in more detail, the rainfall events were divided into four categories according to rainfall duration and intensity.

1) Rainfall duration, frequency, and amount relationships

Table 2 shows the average number of rainfall events and average rainfall amount for each rainfall duration category from June to October 1998 and 1999. Each category was arbitrarily determined by rainfall duration to have a statistically sufficient number of samples. Though some different categorizations were investigated (e.g., changing the 2–5-h category to a 3–4- or 3–
6-h category), no significant differences resulted. Thus, categorization did not affect this paper’s conclusions.

As shown in Table 2, most rainfall events (approximately 95%) lasted less than 5 h. A large number of events lasted approximately 1 h (54.8% in 1998; 56.6% in 1999), though the rainfall amounts from these events accounted for a small percentage of the total observed rainfall (15.0% in 1998; 14.0% in 1999). The 2–5-h category accounted for the greatest rainfall amounts (58.0% in 1998; 55.6% in 1999). Rainfall events that lasted over 6 h contributed a relatively large rainfall amount (around 30%) to the total, though they only accounted for a small number of events (approximately 5%).

Figures 6 and 7 examine the results further and focus, in particular, on spatial characteristics. Figure 6 shows the relationships between elevation and the four rainfall duration categories. Figures 6a–d show the 1-, 2–5-, 6–10-, and over-11-h categories, respectively.

As indicated in Fig. 6a, the number of 1-h rainfall events increased with elevation. The year 1999 had nearly twice as many 1-h rainfall events as 1998, regardless of station elevation. Figure 6b indicates a similar trend. The number of relatively long rainfall events was much smaller than those for the previous two categories (see Figs. 6c and 6d). Nonetheless, a clear correlation exists between the number of rainfall events and elevation. As compared to 1998, the number of rainfall events in 1999 increased only at the high-altitude stations. For longer rainfall duration categories (Figs. 6c and 6d), however, 1998 and 1999 showed no significant differences in the number of low-elevation events.

Figure 7 illustrates the relationships between elevation and rainfall amounts for the categorized events. As shown in Fig. 7a, the rainfall amounts of the shortest duration category did not clearly correlate with elevation. The total rainfall amount for the 1-h category was not large (about 15%, as shown in Table 2), as mentioned above. Figure 7b indicates the major contributor to orographic rainfall. As shown in Figs. 7c and 7d, despite the smaller number of events, the 2–5-h category, as well as the even rarer longer duration category, contributed relatively large amounts to orographic rainfall.

2) Rainfall intensity, frequency, and amount relationships

Table 3 shows the average number of rainfall events and the average rainfall amount for the four intensity-related categories, less than 1, 1–5, 5–11, and over 11 mm h$^{-1}$ from June to October 1998 and 1999. Over 90% of the total rainfall events had rainfall intensities weaker than 5 mm h$^{-1}$. Intensities weaker than 1 mm h$^{-1}$ contributed a large number of events (50.4% in 1998; 52.7% in 1999), but only a small accumulation (8.5% in 1998; 9.6% in 1999).

One can suspect that some part of this frequent very light rain (1 mm h$^{-1}$), is due to dew formation or fog drips. However, it is generally very difficult to catch dewdrops and fog drips by 0.5 mm per tip rain gauge. Fog moves horizontally, and forest canopy can catch it and make drips. But, a rain gauge, which has a simple shape, could not be expected to form them. Convective rains in the evening that quickly pass by a rain gauge would explain some parts of the light rainfall events.

The 1–5 mm h$^{-1}$ intensity category was responsible for the greatest rainfall amounts (54.1% in 1998; 58.0% in 1999). While the number of rainfall events with greater than 5 mm h$^{-1}$ intensities was very small (about 7%–
those rainfall events contributed a relatively large amount of rainfall (over 30%)

Figure 8 shows the relationships between elevation and rainfall events divided into each rainfall intensity category. As shown in Figs. 8a and 8b, elevation and the number of relatively weak rainfall events correlated well. On the other hand, Figs. 8c and 8d show that relatively strong intensity rainfall events showed almost no association with elevation. Only 1999 had weakly correlated events (Fig. 8c). The year 1999 had approximately twice as many relatively weak intensity rainfall events as 1998 (see Figs. 8a and 8b). As Fig. 8c indicates, 1999 had 1.5 times as many comparatively strong rainfall events, though both 1999 and 1998 data showed a little correlation between stronger rain intensities and elevation. There were no significant differences in the number of strong intensity rainfall events between 1998 and 1999, as shown in Fig. 8d.

Figure 9 illustrates elevation and rainfall amount relationships by rainfall intensity category. As shown in Fig. 9a and Table 3, events with less than 1 mm h$^{-1}$ rainfall intensity correlated comparatively well with elevation. However, 1 mm h$^{-1}$ rainfall intensity events contributed little to high elevation rainfall (less than 10%), despite the large number of these events (about 50% of the total). The 1–5 mm h$^{-1}$ rainfall intensity category also correlated well with elevation and was a major contributor to orographic rainfall (see Fig. 9b). The 1–5 mm h$^{-1}$ category contributed over half the rainfall and had a large increment in the linear regression [33.3 mm (100 m)$^{-1}$ in 1998 and 53.9 mm (100 m)$^{-1}$ in 1999]. As shown in Fig. 9c, 1999 strongly contributed to orographic rainfall; however, 1998 did not [9.4 mm (100 m)$^{-1}$ in 1998 and 28.7 mm (100 m)$^{-1}$ in 1999]. Figure 9d indicates that the stronger intensity rainfall events did not contribute to orographic rainfall and had a small increment in the linear regression [less than 2.5 mm (100 m)$^{-1}$]. Although only about 7%–8% of the rainfall events had an intensity greater than 5 mm h$^{-1}$, these rainfall events accounted for a relatively large portion of each station’s rainfall (over 30%). The 1–5 and 5–11 mm h$^{-1}$ rain intensity category showed clear differences between 1998 and 1999, as shown in Fig. 9.

Rainfall events with 1–5 mm h$^{-1}$ intensities occurred most frequently and correlated best with elevation. Strong intensity rainfall events (e.g., over 5 mm h$^{-1}$) were very limited in the number of events. Except for the 5–11 mm h$^{-1}$ rain intensity category in 1999, the large contribution by these events did not correlate with elevation.
Fig. 7. Relationship between elevation and the rainfall amount of each rainfall duration category from Jun to Oct 1998 and 1999.

Table 3. Average number of events, ratio of average number of events to the total, average rainfall amount, ratio of average rainfall amount to the total, increment and coefficient of determination of the linear regression between elevation and frequency, and increment and coefficient of determination of the linear regression between elevation and rainfall amount for each rainfall intensity (I) category from Jun to Oct 1998 and 1999.

<table>
<thead>
<tr>
<th>Rainfall intensity (mm h⁻¹)</th>
<th>I &lt; 1</th>
<th>1 ≤ I &lt; 5</th>
<th>5 ≤ I &lt; 11</th>
<th>11 ≤ I</th>
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<tr>
<td>Average No. of events</td>
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</tr>
<tr>
<td>1998</td>
<td>92.8</td>
<td>76.8</td>
<td>11.3</td>
<td>3.3</td>
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<tr>
<td>1999</td>
<td>147.8</td>
<td>113.2</td>
<td>16.2</td>
<td>3.5</td>
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<td>Ratio of No. of events to total (%)</td>
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<td>1998</td>
<td>50.4</td>
<td>41.7</td>
<td>6.1</td>
<td>1.8</td>
</tr>
<tr>
<td>1999</td>
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<td>1998</td>
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<td>470.8</td>
<td>218.7</td>
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<td>0.77*</td>
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<td>1999</td>
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<td>0.68*</td>
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<td>0.86*</td>
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<tr>
<td>1999</td>
<td>0.52*</td>
<td>0.79*</td>
<td>0.56*</td>
<td>0.06</td>
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</table>

* 1% significance level.
** 5% significance level.
3) RAINFALL DURATION, INTENSITY, FREQUENCY, AND AMOUNT RELATIONSHIPS

Clearly, the data show strong relationships between elevation and the number of events, regardless of rainfall duration (Fig. 6). Relatively long rainfall duration events were responsible for orographic rainfall, as measured in rainfall amounts (Fig. 7). Moreover, the number of weak rainfall intensity events (less than 5 mm h$^{-1}$) significantly correlated with elevation (Figs. 8a and 8b). On the other hand, the number of strong rainfall intensity events (over 5 mm h$^{-1}$) was relatively independent of elevation (Figs. 8c and 8d). Weak rainfall events thus contributed the most to orographic rainfall amounts (Fig. 9). Both 1998 and 1999 showed similar characteristics. Based on these facts, we speculate that relatively weak rainfall intensity events could cause a low-altitude bias in precipitation estimates (spatial sampling error). On the other hand, strong rainfall intensity events that might relate to incoming storms and large-scale weather systems would not cause it.

These results expand on our previous research (Dairaku et al. 2000) and prior knowledge of orographic rainfall structures in the Mae Chaem watershed; rainfall amount enhancement was linked with altitude in the Mae Chaem watershed, and correlations were found with total rainfall durations, but the mean rainfall intensity was found to be independent. In this paper, our research revealed more detailed orographic rainfall structures on an event basis; that is, rainfall events occur frequently and tend to be of long duration (regardless of rainfall intensity) at relatively high altitudes in the watershed.

4. Conclusions

As one of the GAME-T research activities, a dense ground-based rain gauge observation network was established in a northwest Thailand watershed. Gauge observations revealed higher rainfall at higher elevation stations in 1998 and 1999. Observations have traditionally been made only at low elevations and in populated regions, causing one of the errors in estimating areal precipitation. Since the final quality of the merged analysis is primarily determined by the quality of the input data sources, it is necessary to deepen our understanding of bias and error structures in the individual data sources and to better understand rainfall characteristics.

The present study investigated the temporal and spa-
tial distribution, which is one of the important indices reflecting regional hydroclimate conditions. Relating rainfall amount, intensity, duration, and frequency to elevation in the Mae Chaem watershed indicated the following:

1) A strong relationship existed between elevation and the number of events, regardless of an event’s rainfall duration; relatively long rainfall duration events were responsible for orographic rainfall, as measured in rainfall amount.

2) The number of weak rainfall intensity events significantly correlated with elevation, while the number of comparatively strong rainfall intensity events was relatively independent of elevation.

3) Relatively weak intensity rainfall events contributed the most to orographic rainfall amounts.

In conclusion, orographic rainfall characteristics can be attributed to the higher frequency of relatively weak rainfall intensity events at high elevations. These events have longer durations than the stronger rainfall intensity events. These phenomena were common in 1998 and 1999, despite large variation in rainfall amounts between the two years.

During the rainy season, monsoonal moist westerly wind is predominant in the lower troposphere. We presume that the monsoonal background wind and landform rather than synoptic disturbances induce a dynamic orographic upward motion. Therefore convective clouds frequently form in the mountain ranges. The cloud base in the season is around 1.5–2 km above sea level, which is as high as mountains in this region. That is possibly one of the causes of relatively weak and frequent precipitation in the mountain. However, the relationships and associated mechanisms of orographic rainfall characteristics revealed in this study have not yet been thoroughly explained. How do local circulations such as mountain-to-valley circulations interact with Asian monsoon circulations? Questions such as this require further investigation using satellite data for cloud activities, reanalysis atmospheric data, and numerical experiments that can model regional climates using GAME-T gauge observations. Nonetheless, the newly obtained rainfall data and proposed analysis method allow for a better understanding of the tropical mountain climate and its rainfall characteristics and can significantly impact future studies if long-term observations are continued and then applied to other climate regions.

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