An investigation of extreme daily rainfall in the Mekong River Basin using a gridded precipitation dataset

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Abstract:

The objective of this research was to evaluate the applicability of the Asian Precipitation Highly Resolved Observational Data Integration Towards Evaluation of Water Resources (APHRODITE) gridded dataset to develop a spatially distributed extreme daily rainfall map in Southeast Asia. We compared the extreme daily rainfall values of the 5-year return period, estimated by a frequency analysis based on annual maximum rainfall during 1987–2006 from the APHRODITE dataset and rainfall observations from 185 gauges in Thailand, Laos, and Vietnam. It was found that the extreme rainfall values estimated from the APHRODITE dataset are approximately 33–38% less than those estimated from observations at rain gauge stations. When the APHRODITE data were corrected with an appropriate bias correction ratio and elevation factor and then used to estimate extreme daily rainfall, they showed a better match with the extreme daily rainfall estimations from the rain gauge observations. Moreover, our estimations were independently verified with the rainfall observations in the Mae Chaem Watershed (MCW) in Thailand. This study suggests that the APHRODITE dataset can be used to obtain an estimation of the extreme rainfall in the Mekong River countries after proper bias and orographic corrections are made.

KEYWORDS APHRODITE dataset; orographic rainfall; extreme rainfall; return period

INTRODUCTION

Southeast Asian countries such as Thailand have experienced numerous rainfall-induced disasters such as slope failure and flooding, which have caused substantial damage in many regions (Dykes, 2002; Ono et al., 2010). For example, approximately 10 record-breaking floods have occurred since 1978 in the Chao Phraya Delta in Thailand (Thi et al., 2012). One of the largest flood events occurred in 2011, resulting in estimated damages of more than 40 billion USD and more than 800 deaths (Komori et al., 2012). Most of these disasters have been triggered by heavy rainfall. However, minimal efforts have been made to estimate or predict these events. This situation in Southeast Asia can be further exacerbated by the lack of climate data available for scientific analysis. For example, Oki et al. (1999) found that land surface modeling tends to underestimate the annual runoff due to a lower rain gauge density affecting the quality of precipitation predictions.

The prediction of extreme-rainfall-induced hazards requires information on the temporal and spatial distribution of daily extreme rainfall. The estimation of the spatial rainfall distribution is a true challenge, especially in Southeast Asia, with its large topographic variations, because the orographic effect makes the rainfall distribution highly variable (Kuraji et al., 2001, 2009; Gottardi et al., 2012). Yatagai et al. (2009) developed a gridded precipitation dataset in the Asian Precipitation–Highly Resolved Observational Data Integration Towards Evaluation of Water Resources (APHRODITE) project, which was the first rainfall dataset produced to cover the entirety of Southeast Asia with long-term daily rainfall data. This dataset was derived with new interpolation techniques that consider daily precipitation climatology and local topography features; doing so enables many types of studies (Kamiguchi et al., 2010). For example, Kamiguchi et al. (2010) reported on the applicability of the APHRO_JP precipitation product, which has a resolution of 0.05° × 0.05°, for both mean and extreme precipitation in the Japanese land area. However, care should be taken when using the APHRODITE dataset in Southeast Asia because it has a resolution of 0.25° × 0.25°, regressed from its raw resolution (0.05° × 0.05°) due to a data policy of not releasing raw data (Yatagai et al., 2012). Therefore, as the result of this regridding process, the APHRODITE dataset could contain spatially averaged rainfall values (25 grid cells to be averaged to define each 0.25° grid value), and these values are generally less than the values directly measured by rain gauges. The regressed value is reasonable as a representative value in the 0.25° grid; however, it is inappropriate to estimate extreme rainfall-induced disasters because lower rainfall values would lead to more optimistic or “liberal” estimations rather than to pessimistic or “conservative” estimations, which should be avoided in hydrological disaster simulations. Moreover, due to its coarse resolution, the APHRODITE data in Southeast Asia should be downscaled to match the local rainfall patterns, including the orographic effect.

The objective of this study is 1) to propose a methodology of bias and orographic correction on the APHRODITE dataset in Southeast Asia in terms of extreme rainfall values and 2) to evaluate the applicability of the APHRODITE dataset for developing a spatially distributed extreme rainfall map in the Mekong River countries. This study can give researchers insight into the potential use of the APHRODITE dataset for hydrological modeling in extreme rainfall events.

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STUDY AREA AND DATASET

Climate in study area

Three study areas in Thailand, Laos, and Vietnam were selected based on the long-term data availability. The study area has a tropical climate with a monthly mean temperature that varies from 27.6°C in December to 31.6°C in April. The rainy season starts with the southwest monsoon period. For example, in Thailand, the southwest monsoon brings at least 68% of the total annual precipitation (1023 mm yr⁻¹) and causes heavy flooding in the river valleys from June to October.

Gauged rainfall data

The daily rainfall data over a period of 20 years (1987–2006) were taken from 150 rain gauges of the Thailand Meteorological Department (TMD) in Thailand and from 30 and 5 rain gauges of the Mekong River Commission (MRC) in Laos and Vietnam, respectively. Figure 1 shows the location of the 185 rain gauges. All of the 185 rain gauges were incorporated into the APHRODITE dataset. The rain gauges were selected because they assured their accuracy via quality controls and did not include consecutive errors over a one week. Moreover, the daily rainfall data for 15 years (1998–2012) from 6 rain gauges in the Mae Chaem Watershed (MCW) in Thailand, which were not incorporated into the APHRODITE dataset, were used to assess the applicability of our estimations.

Gridded daily rainfall data

The APHRODITE dataset Ver.1003R1 for Monsoon Asia released in August 2010 (available at http://www.chikyu.ac.jp/precip/index.html), which covers 57 years (1951–2007), was used to obtain gridded daily rainfall data. This dataset covers an area of 60.0 E to 150.0 E and 15.0 S to 60.0 N and has a resolution of 0.25° × 0.25° (decimal degrees). Matching the available data period with the 185 rain gauges, the APHRODITE data from 1987 to 2006 were used.

Elevation data

HYDRO1k, from the United States Geological Survey (USGS), was used for elevation data (available at http://eros.usgs.gov/products/elevation/hydro1k.html). These data have a horizontal resolution of 1 km × 1 km and a vertical resolution of 1 m. The highest elevation we used in the study area was 2565 m m.s.l. at Doi Inthanon, northwestern Thailand. For the analysis in the present study, this original grid of 1 km × 1 km was regridded to 0.05° × 0.05°. Figure 1 shows the elevation in the study area.

METHODOLOGY

The APHRODITE dataset was developed based on an international data collection process incorporating the 185 rain gauges from TMD and MRC in the respective countries. For the evaluation of the extreme rainfall in the study area, we compared the APHRODITE dataset with rainfall observations from not only the TMD and MRC rain gauges but also rain gauges in the MCW. To evaluate the bias in the APHRODITE dataset, the extreme rainfall values of the 5-year return period estimated from the APHRODITE dataset and the rain gauges were compared in each grid cell. The whole dataset was divided into two sets for which the analysis from the Thailand records was performed first and then the data from Laos and Vietnam were collectively used for verification. The working procedure for estimating the daily extreme rainfall for a particular return period is as follows (we considered the 5-year return period only): (a) extraction of annual maximum daily rainfall for 20 years (1987–2006, except MCW) from all of the rain gauge stations and the APHRODITE grids, (b) frequency analysis based on the extracted annual maximum daily rainfall values of the APHRODITE data and the rain gauge data to estimate the extreme daily rainfall distribution in Southeast Asia, a frequency analysis for each grid cell was performed based on annual maximum daily rainfall values from the APHRODITE dataset and the rain gauge data to estimate the extreme daily rainfall of the 5-year return period, (c) comparison of the extreme daily rainfall in the 5-year return period between the APHRODITE grids and the rain gauges, and (d) bias correction and incorporation of orographic rainfall.

Frequency analysis

We followed the methodology in Kawagoe et al. (2010) to estimate daily extreme rainfall for different return periods. They used the General Extreme Value (GEV) probability distribution function and the Probability Weight Moment (PWM) method as a universal prediction method. To estimate the daily extreme rainfall distribution in Southeast Asia, a frequency analysis for each grid cell was performed based on annual maximum daily rainfall values from the APHRODITE dataset. For comparison, the same frequency analysis was performed for the rain gauge data. The GEV is commonly used for estimating the return period of extreme rainfall and flood events (Martins and Stedinger, 2000). An explanation of GEV analysis and the PWM method for parameter calibration can be found in Kawagoe et al. (2010).
Bias corrections

The bias correction was performed based on Equation (1):

$$ExP_{bias} = [(100\%) / (100\% - Bias)] ExP$$ (1)

where $ExP$ is the extreme daily rainfall in the APHRODITE dataset (mm $d^{-1}$), $ExP_{bias}$ is the value after the bias correction (mm $d^{-1}$), and $Bias$ is the bias in the extreme rainfall values in the APHRODITE dataset compared with rain gauge observations (%).

Orographic corrections

Firstly, a regression equation (2) was developed based on the 150 TMD rain gauges between the extreme daily rainfall with the 5-year return period and topographic variations, considering elevation and latitude as the independent parameters. As a result, the extreme rainfall of the 5-year return period was expressed by:

$$ExP_{RG} = \beta_{Ele} Ele + \beta_{Lat} Lat + b$$ (2)

where $ExP_{RG}$ is the extreme daily rainfall of the 5-year return period (mm $d^{-1}$), $Ele$ is the elevation (m), $Lat$ is the latitude (decimal degrees), $\beta_{Ele}$ is the coefficient of elevation, $\beta_{Lat}$ is the coefficient of latitude, and $b$ is the intercept. Moreover, given an extreme rainfall distribution result, which will be described in a later section, in which the APHRODITE dataset showed the latitude’s effect but not the elevation’s effect, a new parameter $\alpha$ was defined to incorporate this orographic effect in the distribution of extreme rainfall of the 5-year return period:

$$\alpha = (\beta_{Ele} Ele + \beta_{Lat} Lat + b) / (\beta_{Lat} Lat + b)$$ (3)

where $\alpha$ denotes the ratio of the orographic rainfall in the extreme daily rainfall of the 5-year return period in Thailand, which is expected to address the orographic effect in each area. The parameter $\alpha$ was calculated using elevation data with a resolution of 0.05° $\times$ 0.05° as an input for downscaling. The gridded elevation data with its locations (latitudes and longitudes) was substituted into Equation (3). Secondly, the extreme rainfall distribution at a 0.25° $\times$ 0.25° resolution obtained based on the APHRODITE dataset was regridded to a 0.05° $\times$ 0.05° scale using a linear interpolation method to match the spatial scale of the elevation data. Finally, by applying the parameter $\alpha$ to the regridded rainfall distribution, the distribution of the extreme rainfall was estimated:

$$ExP_{oro} = \alpha ExP_{bias}$$ (4)

where $ExP_{oro}$ is the extreme daily rainfall of the 5-year return period after bias and orographic correction (mm $d^{-1}$). In this way, errors in extreme rainfall estimation due to local scale topography variations can be minimized.

RESULTS AND DISCUSSION

Figure S1 shows the overall trend of monthly and annual rainfall in Thailand derived from the 150 rain gauge stations and the APHRODITE grids. The figure shows that the monthly and annual rainfall of the APHRODITE dataset is approximately 10–20% less than that of the rain gauges. Figure 2 shows a comparison of the extreme daily rainfall of the 5-year return period estimated by a frequency analysis using the annual maximum daily rainfall based on rain gauge records (20 years $\times$ 150 stations) and the APHRODITE gridded dataset (20 years $\times$ 150 grids) in Thailand without any corrections. The extreme rainfall for the APHRODITE dataset is approximately 38% less than that of the rain gauges. Figure 2 also shows that most of the plots are near the regression line, showing that the bias equally exists among all of the grids with a determination coefficient of 0.64.

In the Japanese land area, Kamiguchi et al. (2010) found the characteristics of the APHRODITE dataset to be as follows: (a) monthly precipitation in the APHRO_JP data and rainfall data from surface observatory stations showed a very similar trend, and (b) APHRO_JP can be used to determine heavy precipitation up to approximately 150 mm $d^{-1}$ for statistical extreme analysis. The characteristic (a) indicates that the interpolation method of the APHRODITE dataset is likely to preserve the monthly climatology of the rain-gauged rainfall, and it should be the same for the APHRODITE dataset in Southeast Asia. Therefore, the reason for the bias in the monthly rainfall values in the APHRODITE dataset could be the regridding process. The regridding process and characteristic (b) might be the reasons for the bias in the extreme rainfall values in the APHRODITE dataset because Thailand, which has a tropical climate, generally experiences extreme rainfall events that are heavier than 150 mm $d^{-1}$ more often than Japan does.

Bias corrections

According to Figure 2, the extreme daily rainfall values of the 5-year return period estimated from the annual maximum daily rainfall of the grid precipitation of the APHRODITE dataset were 38% less than the values from the rain gauge dataset. The bias correction was performed based on Equation (1).

$$ExP_{bias} = [(100\%) / (100\% - 38\%)] ExP$$ (5)

The estimated extreme daily rainfall of the 5-year return period is shown in Figure 3. The results of the extreme rainfall in Figure 3 are as follows: (a) The largest amount
of rainfall was found in a mountainous part of the Malay Peninsula. This result possibly reflects the fact that the heavy rainfall is caused by the interaction between topography and water vapor flux. For example, the extreme rainfall in the Malay Peninsula is greater than 180 mm d$^{-1}$, whereas the value in the central fan around Bangkok is only approximately 120 mm d$^{-1}$, and (b) Although it is known that there is orographic rainfall in Thailand, significant orographic rainfall around mountainous regions was not found. For example, Dairaku et al. (2004) found that the extreme daily rainfall in the northern mountains is often over 200 mm d$^{-1}$, but Figure 3 depicts a value of only approximately 120 mm d$^{-1}$.

**Orographic corrections and verifications in the MCW**

Table SI shows the results of the regression analysis in Equation (2), which yields a positive relationship with elevation, confirming the orographic effect on extreme rainfall with a statistically significant correlation ($p < 0.01$). The negative relationship between extreme rainfall and latitude is expected because areas near the equator (low latitude area) receive high rainfall amounts due to water availability through enhanced evapotranspiration and rapid convection.

Figure 4 shows the spatial distribution of parameter $\alpha$ to account for the effect of topographic variation on the extreme rainfall distribution. The value of $\alpha$ is 1.0 when the orographic rainfall is negligible. The value of $\alpha$ in the northern mountains exceeds 1.75, reflecting significant orographic rainfall. Figure 5 shows the distribution of extreme rainfall, including the orographic effect. In Figure 5, a large amount of extreme rainfall attributed to orographic rainfall was found in several high elevation areas, i.e., in the Malay Peninsula and the northern part of Thailand. It is important to validate these estimations using additional rain gauges in mountainous regions; therefore, the orographic rainfall results were compared with rainfall observations in
the MCW in Thailand.

The Global Energy and Water Cycle Experiment (GEWEX) Asian Monsoon Experiment-Tropics (GAME-T) research project collected high-spatial-resolution ground-based rainfall observations in the MCW in Thailand (Figure 5). Fifteen rain gauges were installed with 1 sec time resolutions at sites ranging from 380 to 2565 m above sea level. Research found that the observed rainfall in mountain ranges was occasionally twice as much as the rainfall in the plains due to its longer duration (Dairaku et al., 2004).

Figure 6a shows the topography and location of the 6 rain gauges we used in the MCW. Figures 6b and 6c are the distribution of extreme rainfall of the 5-year return period derived from APHRODITE data with and without the bias and orographic correction that we proposed. Table SII shows the names, codes, and altitudes of the 6 rain gauges. According to our estimations in the MCW (Figure 6c), the extreme daily rainfall in low-elevation areas and in mountain ranges is approximately 90 mm d$^{-1}$ and 180 mm d$^{-1}$, respectively, confirming the applicability of our results with the Dairaku et al. (2004) estimations.

Figure 7 compares the extreme daily rainfall of the 5-year return period derived from the 6 rain gauges in the MCW and APHRODITE data. The figure shows, after bias and orographic correction, that the estimations from the APHRODITE dataset better match the estimations based on the observations from the rain gauges, especially at a high elevation (i.e., DO: Doi Inthanon station). For example, in Doi Inthanon station, the original value (70 mm d$^{-1}$) was increased up to 97 mm d$^{-1}$ after the bias correction and then up to 180 mm d$^{-1}$ after both bias and orographic correction. This result indicates that the orographic correction can be applicable for higher elevations than the area where the regression equation (2) was developed.

**Applications in Laos and Vietnam**

Figure 8 shows a comparison of the extreme daily rainfall of the 5-year return period derived from the APHRODITE dataset and the observations from MRC rain gauges in Laos and Vietnam (35 stations). Similar to the results in Thailand, the extreme daily rainfall values of the grid precipitation of the APHRODITE dataset are less than that of the MRC rain gauge. Overall, the extreme rainfall values of the grid precipitation of the APHRODITE dataset are approximately 33% less than that estimated from the observations at the MRC rain gauge stations. This bias of 33% is similar to the one estimated in Thailand (38%), and the difference implies that the bias depends on the region. Given this similarity, it is worth considering the possibility of using a common bias correction ratio for the Mekong river countries because, from a practical perspective, it is often difficult to quantify
the bias in each country due to limited data availability.

The practical applications of this study depend on the potential usefulness of the APHRODITE dataset for estimating extreme rainfall in the Mekong River Basin. As such, the same methodology with a common bias correction ratio (38%) was applied to the data in Laos and Vietnam. Similar to the data analysis in Thailand, the extreme rainfall values of the 5-year return period estimated from the APHRODITE data were bias corrected according to Equation (1) and then corrected for the orographic effect using Equations (3) and (4).

Figure 8 compares the extreme daily rainfall of the 5-year return period derived from the MRC rain gauge data and the bias and orographic corrected APHRODITE data. The figure indicates that, after bias and orographic correction, the estimations from the APHRODITE dataset better match the estimations based on the observations from the rain gauges. The figure also shows that the extreme rainfall values of the 5-year return period derived from the APHRODITE dataset are generally more than that from the rain gauges. This over-estimation is most likely to be attributed to the rain shadow effect in mountainous areas. The southwest monsoon wind, which brings approximately 70% of the total annual precipitation in Thailand, blows from the Andaman Sea to the main regions of Thailand. The mountain range near the border of Thailand and Laos uplifts wet and saturated air during the southwest monsoon period, and it results in an increased rainfall in northern Thailand while a decreased rainfall in Laos on the leeward slopes of the mountain range. This phenomenon implies that the orographic correction ratio depends on specific regions, suggesting the limitation of the orographic correction method developed in Thailand.

CONCLUSIONS

The extreme daily rainfall of the 5-year return period, which was estimated from the annual maximum rainfall of the APHRODITE dataset, was approximately 33–38% less than that estimated from the observations at the rain gauge stations in the three countries. When the APHRODITE data were corrected with the appropriate bias correction ratio and elevation factor and then used to estimate extreme daily rainfall with a 5-year return period, they showed a better match with the 5-year extreme daily rainfall estimations from the rain gauge observations. In the MCW, after the bias and orographic correction, the estimations from the APHRODITE dataset better match the estimations based on the observations from the rain gauges, especially at higher elevations. Although further validation is needed, this study suggests that the APHRODITE dataset could potentially be used for estimating the extreme rainfall in the Mekong River Basin after proper bias and orographic corrections are made.

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SUPPLEMENTS

Figure S1. Monthly and annual rainfall in Thailand derived from the 150 rain gauge stations and the APHRODITE grids. The vertical axes represent monthly rainfall (mm mon<sup>-1</sup>) and annual rainfall (mm yr<sup>-1</sup>).

Table S1. Results of the regression analysis.

Table SII. Station name, code, altitude, and location.

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