Climate **2015**, *3*, 168-192; doi:10.3390/cli3010168

OPEN ACCESS

climate

ISSN 2225-1154

www.mdpi.com/journal/climate

Article

Regional Observed Trends in Daily Rainfall Indices of Extremes over the Indochina Peninsula from 1960 to 2007

Muhammad Yazid [1,2] and Usa Humphries [1,*]

1 Department of Mathematics, King Mongkut's University of Technology Thonburi, Bangkok 10140, Thailand; E-Mail: azid26@gmail.com

2 Environmental Science, Graduate Program of Mulawarman University, Samarinda 75123, Indonesia

* Author to whom correspondence should be addressed;
E-Mail: usa.wan@kmutt.ac.th or azid26@gmail.com; Tel.: +662-470-8831

Academic Editor: Monica Ionita-Scholz

Received: 23 September 2014 / Accepted: 10 February 2015 / Published: 17 February 2015

Abstract: This study analyzed the trends of extreme daily rainfall indices over the Indochina Peninsula from 1960 to 2007. The trends were obtained from high-resolution gridded daily rainfall data compiled by APHRODITE with coordinates of 4°N–25°N and 90E°–112°E. The indices were selected from the list of climate change indices recommended by ETCCDI, which is a joint group of WMO CCl, CLIVAR and JCOMM. The indices are based on the number of heavy rainfall days (≥10 mm), number of very heavy rainfall days (≥20 mm), number of extremely heavy rainfall days (≥25 mm), consecutive dry days (<1 mm), consecutive wet days (≥1 mm), daily maximum rainfall, five-day maximum rainfall, annual wet-day rainfall total, Simple Daily Intensity Index, very wet days, and extremely wet days. The indices were simulated by calculating different extreme characteristics according to wet and dry conditions, frequency, and intensity. Linear trends were calculated by using a least squares fit and significant or non-significant trends were identified using the Mann–Kendall test. The results of this study revealed contrasting trends in extreme rainfall in eastern and western Indochina Peninsula. The changes in extreme rainfall events in the east primarily indicate positive trends in the number of heavy rainfall days, very heavy rainfall days, extremely heavy rainfall days, consecutive wet days and annual wet-day rainfall total, with significant trends at times. These events correlated with the northeastern monsoon that influences the Indochina Peninsula from October to February annually. The results in the west primarily indicate negative trends in consecutive wet days, where significant trends were correlated with decreasing number of annual wet-day rainfall total, heavy rainfall days, very heavy rainfall days, and extremely heavy rainfall days. Daily maximum rainfall, five-day maximum rainfall, very wet days, and extremely wet days show random positive (negative) significant (non-significant) trends, while the simple daily intensity index shows positive trends that dominate the southern part of the Indochina Peninsula, with some grids show significant trends.

Keywords: extreme rainfall events; frequency; indices; Indochina Peninsula; intensity

---

1. Introduction

Uncertainty of monsoons over the past decade has resulted in climate variability and disastrous floods in the Indochina Peninsula countries. Historical analysis of extreme rainfall is needed to design mitigation strategies. The specific goal of this study is to provide a description of the extreme rainfall phenomena based on the statistical trends in extreme rainfall indices and the characteristics of its distribution.

The Indochina Peninsula is an area in Southeastern Asia, including Thailand, Cambodia, Laos, Vietnam, Myanmar, and small parts of Malaysia. Many disastrous events resulting from extreme rainfall occur in this area, including the Upper Mekong Countries of China, Laos, Myanmar, Thailand, and in the northeastern, central and southern parts of Malaysia [1].

Studies on extreme climate events have been conducted in areas, such as in Asia [2,3], Europe [4], America [5,6], Africa [7], and Australia [8–10], which typically were preceded by workshops coordinated by the Expert Team on Climate Change Detection and Indices (ETCCDI). Consequently, a team was formed by the Commission on Climate Variability and predictability (CLIVAR) under the auspices of the World Meteorological Organization (WMO).

Choi *et al.* (2009) conducted studies on extreme rainfall events in Asia Pacific [11]. They used 143 weather stations in ten Asia-Pacific Network (APN) countries to study the spatial and temporal change patterns in extreme temperature and precipitation events and their associations with the changes in climate means. Yin *et al.* (2014) compared five gridded datasets included in APHRODITE in measuring the temperature and precipitation extremes over China in the last five decades [12]. Little research on extreme rainfall has been completed for the Indochina Peninsula. Therefore, it is necessary to study the trends of extreme rainfall events in the Indochina Peninsula.

Changes in the frequency and intensity of extreme rainfall are a serious problem for human lives [13], often resulting in strong winds, lightning and floods [14]. Many extreme events will become more numerous in the 21st century [15], influencing the policy determination in many sectors, such as economic development [13], agriculture management, infrastructure (construction management), and others [16,17]. Thus, we will know whether the strategies or policies that have been made are appropriate with the present and future extreme climate conditions with this research.

2. Methods

2.1. APHRODITE Datasets

In this study, indices of extreme rainfall events were generated using series data. Rainfall period data are imperative in determining extreme rainfall events [18]. A long rainfall period with daily resolutions is needed to estimate the frequency and intensity of extreme rainfall events [13].

The data used in this study were obtained from Asian Precipitation-Highly-Resolved Observational Data Integration towards Evaluation of Water Resources (APHRODITE) datasets for a 48-year period from 1960 to 2007. These gridded data were extracted from station data, precompiled data, and the Global Telecommunication System (GTS) [19]. The data have gone through 14 quality control (QC) processes, controlling for erroneous values, duplication, repetition, homogeneity, and others [20].

Kamiguchi *et al.* (2010) and Yatagai *et al.* (2012) studied the effect of gauge network changes on long-term trends, including extreme values, and they found that a change in gauge density does not affect the total rainfall trend but does affect the trend of extreme values in Japan [20]. Thus, this research used the gridded APHRODITE dataset with a spatial resolution of 0.5° × 0.5° to observe the extreme rainfall trends over the Indochina Peninsula (Figure 1).

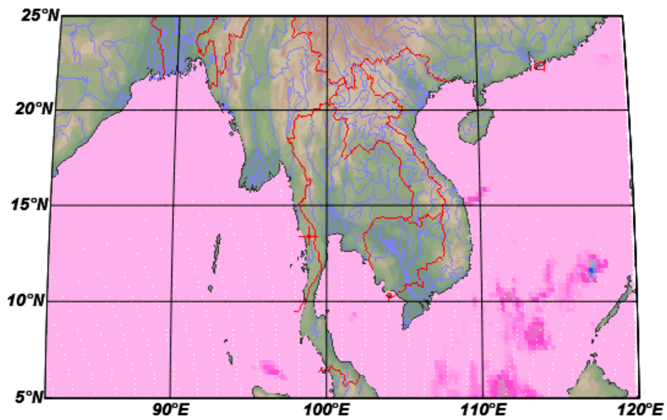


Figure 1. The study domain, defined as the Indochina Peninsula.

2.2. Extreme Rainfall Indices

The analysis of extreme rainfall events was adapted from WMO (2009), Santos *et al.* (2009) [5] and Zhang *et al.* (2011) [21] and determined by several indices that are used widely in determining extreme weather events. The indices were selected from the list of climate change indices recommended by World Meteorological Organization-Commission for Climatology (WMO-CCI) and the research program on Climate Variability and Predictability (CLIVAR) and JCOMM. Table 1 defines the extreme rainfall indices used in this study [1,5,13].

The rainfall data were processed using the RClimDex software package to calculate indices and trends. The RClimDEX software package is an R-language software package developed by the CCI-CLIVAR Expert Team for Climate Change Detection and Indices (ETCCDI) to detect and monitor extreme climate events; the package is available at http://etccdi.pacificclimate.org/index.shtml.

Table 1. Definition of indices.

Indices	Name	Indices Calculation	Definition	Unit
Frequency Indices (adapted from WMO 2009 and Santos *et al.* 2009[5,13])				
R10m	Number of heavy rainfall days	$RR_{ij} \geq 10mm$	Annual count of days when days rainfall ≥ 10 mm	Days
R20m	Number of very heavy rainfall days	$RR_{ij} \geq 20mm$	Annual count of days when days rainfall ≥ 20 mm	Days
R25m	Number of extremely heavy rainfall days	$RR_{ij} \geq 25mm$	Annual count of days when days rainfall ≥ 25 mm	Days
CDD	Consecutive dry days	$RR_{ij} < 1mm$	Maximum number of consecutive days with RR < 1 mm	Days
CWD	Consecutive wet days	$RR_{ij} \geq 1mm$	Maximum number of consecutive days with RR ≥ 1 mm	Days
Intensity Indices (adapted from WMO 2009 and Santos *et al.* 2009 [5,13])				
RX1day	Daily maximum rainfall	$Rx1day_j = \max(RR_{ij})$	Monthly maximum 1-day rainfall	Mm
RX5day	5-day maximum rainfall	$Rx5day_j = \max(RR_{ij})$	Monthly maximum 5-day rainfall	Mm
PRCPTOT	Annual wet-day rainfall total	$PRCPTOT_j = \sum_{i=1}^{1} RR_{ij}$	Annual total rainfall in wet day (RR > 1 mm)	Mm
SDII	Simple daily intensity index	$SDII_j = \frac{\sum_{w=1}^{W} RR_j}{W}$	Annual mean rainfall when PRCP ≥ 1 mm	Mm/day
R95p	Very wet day	$R95p_j = \sum_{W=1}^{W} RR_{wj}$	Annual total rainfall when RR > 95 percentile	Mm
R99p	Extremely wet day	$R99p_j = \sum_{W=1}^{W} RR_{wj}$	Annual total rainfall when RR > 99 percentile	Mm

RR = Rainfall on consecutive days.

2.3. Temporal Trend Analysis

Many techniques can be used for analyzing the series data trends, yet the most commonly used technique by meteorologists is the Mann–Kendall test. Several studies used the Mann-Kendall test for trend analyses, such as Yazid *et al.* (2014), Santos *et al.* (2012), Fu *et al.* (2010), and Zhang *et al.* (2001) [1,5,10,22]. The principle of the Mann–Kendall is to test observational data by arranging the data into a time series and calculating the differences between the observational data and the nearest data.

The Mann-Kendall test is non-parametric, does not require normally distributed data, and has a low sensitivity to missing data. Null hypothesis H_0 means that no trend changes in series data have been found (the data are independent and randomly ordered), and H_0 is tested against the alternative hypothesis H_1, which assumes a trend exists.

2.4. Spatial Analysis

Spatial analysis is beneficial for hydrological models and disaster management. The research presented here required a technique to analyze the spatial characteristics of extreme rainfall events. A popular technique is the interpolation method. The basic principle of the interpolation method is to assume that the short distance value is considered over the far distance value. Subyani *et al.* (2004) [23] analyzed many interpolation methods that could be used to analyze spatial characteristics of rainfall data.

In term of the ability to fit with the data and produce smoother surface, this research used the Radial Basis Function technique to interpolate 248 grids over the mainland of the Indochina Peninsula. The Radial Basis Function technique is exact interpolator and quite flexible because it generates the best overall interpretation of most datasets. Additionally, this technique is appropriate for the number of interpolation data grid ranges between 250–1000 and produces an appropriate representation of the data.

3. Results and Discussion

The following figures are the monthly mean rainfall patterns from 1960 to 2007 (48-year period) over the Indochina Peninsula. Figure 2 displays the monthly mean rainfall in the northeastern monsoon period (December to March), showing low intensity rainfall of less than 8 mm/day, and in the southwestern monsoon period (June to September), showing high intensity rainfall of greater than 20 mm/day. The studied areas include the western coast of Indochina, the eastern coast of Indochina, and along the coast of southern Thailand.

During the northeastern monsoon, many areas, such as Thailand, experience high wind velocities. The sky in this area tends to be overcast in December and January and experiences rainfall on consecutive days, which may be indicated as extreme rainfall. Meanwhile, this area is quite dry in February and March. During the southwestern monsoon, heavy rainfall occurs from morning through mid-day. Strong winds also occur in this area, usually in the morning. Other time periods are classified as the pre-northeastern monsoon (October–November) and the pre-southwestern monsoon (March to May). The wind speed is quite slow with some light rainfall during these pre-monsoon periods.

3.1. Mean Climatology of Annual Indices

The annual indices were calculated annually, or only one index value per year. Thus, this study had 48 index values from 1960 to 2007. Each grid was averaged and then interpolated to obtain the mean climatology of annual indices to perform the spatial analysis of each index. Both frequency and intensity indices were calculated and subsequently mapped. Frequency indices comprise CDD, CWD, R10mm, R20mm, and R25mm, while the intensity indices comprise RX1day, RX5day, PRCPTOT, R95p, R99p, and SDII.

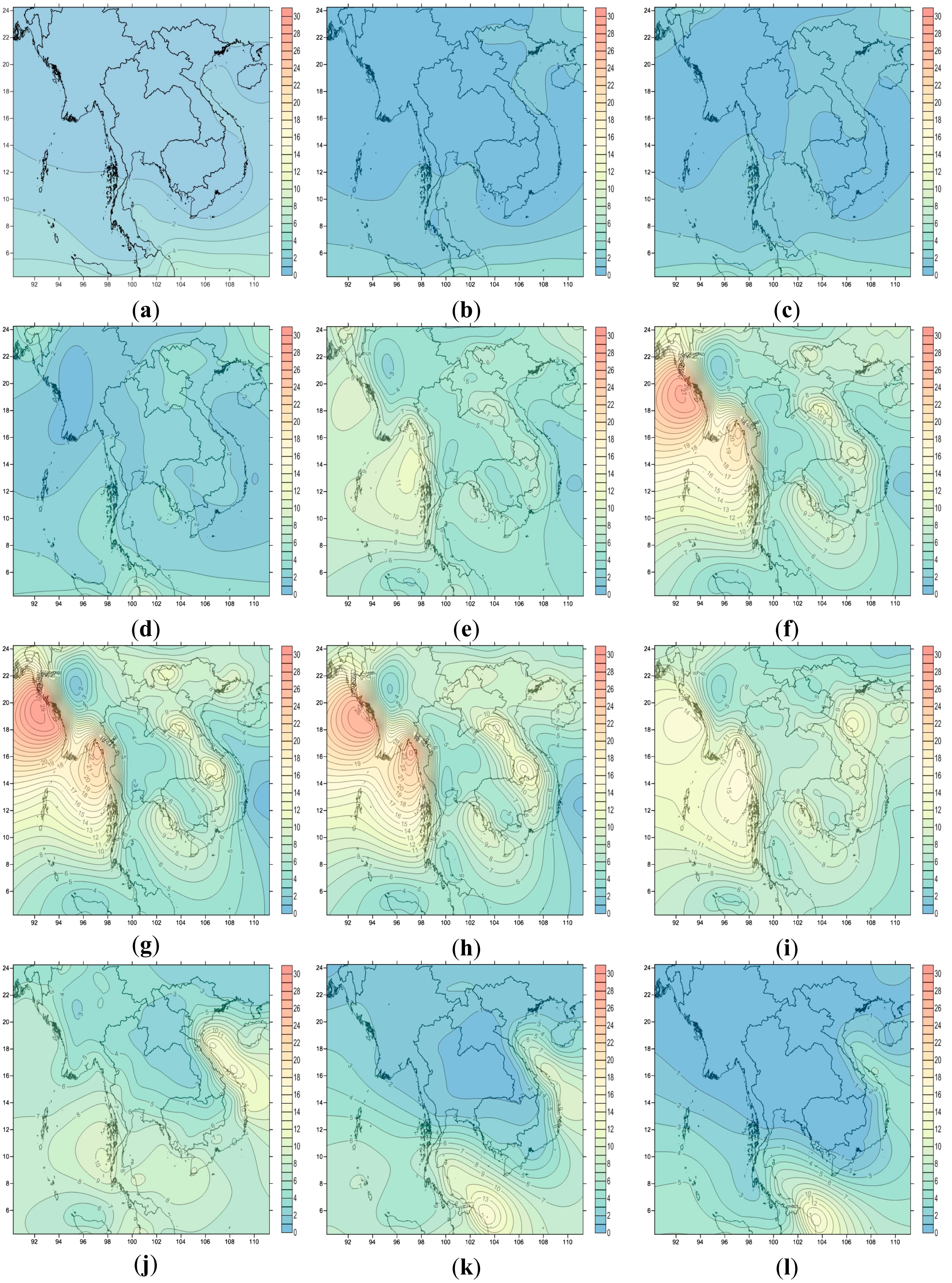


Figure 2. Spatial analysis of monthly mean rainfall over the Indochina Peninsula (mm/day). (**a**) January; (**b**) February; (**c**) March; (**d**) April; (**e**) May; (**f**) June; (**g**) July; (**h**) August; (**i**) September; (**j**) October; (**k**) November; (**l**) December.

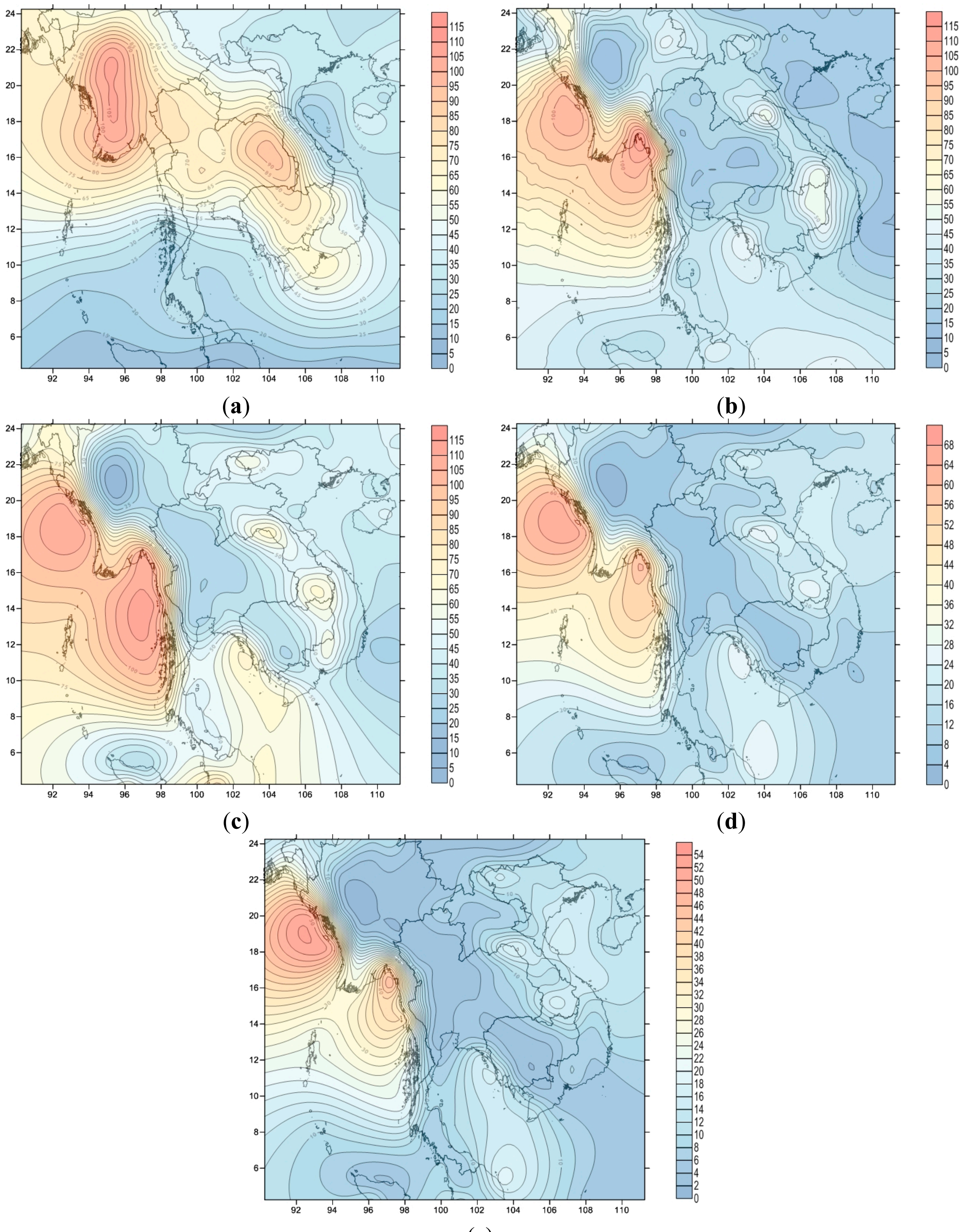


Figure 3. Spatial analysis of frequency indices of mean climatology over the Indochina Peninsula (Days). (**a**) CDD; (**b**) CWD; (**c**) R10mm; (**d**) R20mm; (**e**) R25mm.

3.1.1. Frequency Indices

The consecutive dry days (CDD) index in the Indochina Peninsula has a range of 8–110 days each year (Figure 3a). The lowest number of consecutive dry days is at the latitude-longitude coordinate point of 101.25–4.25 with a total of 8 days, while the greatest number of consecutive dry days is at the point of 95.25–18.25 with a total of 110 days. The area with largest number of consecutive dry days is located primarily on the western coast of the Indochina Peninsula, including in Myanmar, northern Thailand and northern Cambodia. Meanwhile, the eastern coast of the Indochina Peninsula, extending from southern China to Vietnam, southern Thailand and a small part of Malaysia, experiences a low frequency of consecutive dry days [1].

Figure 3b shows the spatial pattern of the consecutive wet days (CWD) index with a range of 11–111 days each year. The lowest number of consecutive wet days is at the point of 106.25–20.35 with a total of 11 days, while the greatest number of consecutive wet days is at the point of 97.25–17.35 with a total of 111 days. The portion of the Indochina Peninsula that covers the entirety of Vietnam, Thailand, Laos, and Cambodia has consecutive wet days with a range of 11–40 days and consecutive wet days of more than 55 days in the coastal areas of Myanmar [1].

The annual frequency of the heavy rainfall day (R10mm) index has a range of 11–111 days each year (Figure 3c). The lowest number of heavy rainfall days is at the point of 95.25–21.25 with a total of 11 days, while the highest number of heavy rainfall days is at the point of 97.25–16.25 with a total of 111 days. This pattern is similar to the CWD index with the number of consecutive wet days and heavy rainfall days primarily located on the western coast of Myanmar and in the coastal area of Cambodia. The number of heavy rainfall day ranges from 11 to 42 days in the mainland of the Indochina Peninsula, including Myanmar, northern Thailand and northern Cambodia.

The annual frequency of very heavy rainfall day (R20mm) and extremely heavy rainfall day (R25mm) indices have similar patterns with ranges of 2–66 days and 1–52 days, respectively (Figure 3d,e). The lowest number of days for these two indices is situated at the point of 95.25–21.25 with a total of two days for the R20mm index and one day for the R25mm index. Meanwhile, the highest number of days is situated at the point of 97.25–16.25 with a total 66 days for the R20mm index and at the point of 94.25–18.25 with a total of 52 days for the R25mm index. The highest number of days for both indices is situated primarily around the northern coast of Myanmar, whereas other regions, such as Myanmar, Thailand, Laos, Cambodia and Vietnam, have a lower number of days with a range of 1–24 days.

3.1.2. Intensity Indices

The mean climatology of daily maximum rainfall (RX1day) in this area has a range from 28 to 146 mm/day as shown in Figure 4a. The lowest intensity of daily maximum rainfall is at the point of 95.25–21.25 with 28 mm/day, while the highest intensity is at the point of 106.25–18.25 with 146 mm/day. The areas with the highest intensity are situated in three places, including the eastern coast of northern Vietnam, the eastern coast of southern Thailand (border with Malaysia), and the western coast of northern Myanmar (border with Bangladesh), whereas other regions have lower intensity of maximum rainfall ranges from 28 to 65 mm/day.

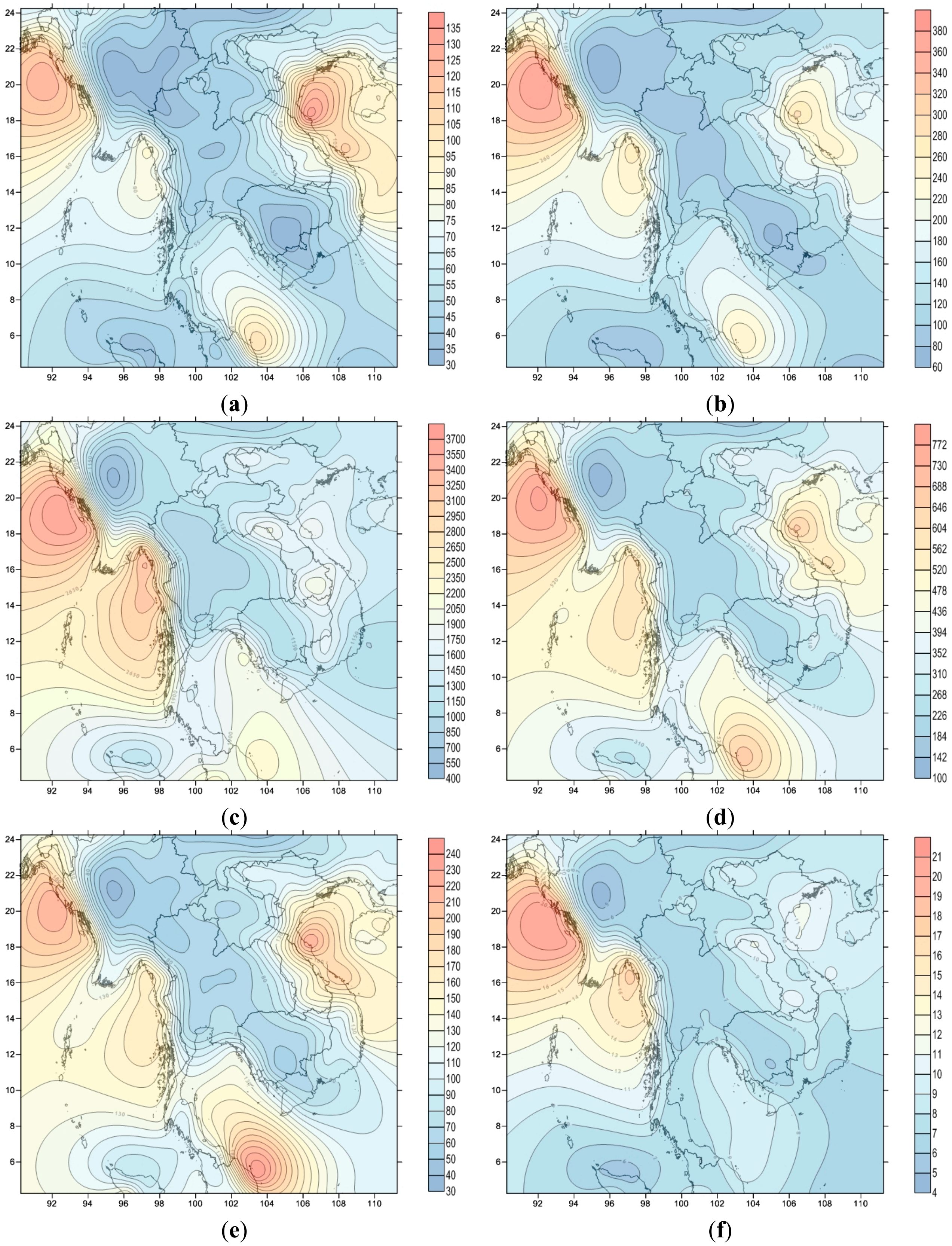


Figure 4. Spatial analysis of intensity indices of mean climatology over the Indochina Peninsula (Mm). (**a**) RX1day; (**b**) RX5day; (**c**) PRCPTOT; (**d**) R95p; (**e**) R99p; (**f**) SDII.

The mean climatology of the 5-day maximum rainfall (RX5day) varies from 65 to 376 mm (see Figure 4b). The resulting pattern is similar to the RX1day index, which is situated in three places, including the eastern coast of northern Vietnam, the eastern coast of southern Thailand (border with Malaysia), and the western coast of northern Myanmar (border with Bangladesh), whereas other regions have a lower intensity of five-day maximum rainfall ranges from 65 to 180 mm. The lowest intensity of the RX5day index is at the same grid point of 95.25–21.25 as the RX1day index with an amount rainfall of 65 mm, while the highest intensity is on a grid of 92.25–21.25 with a rainfall amount 376 mm.

The mean climatology of the annual wet-day rainfall total (PRCPTOT) varies from 503 mm, which is at the point of 95.25–21.25, to 3670 mm, which is at the point 94.25–18.25 (Figure 4c). The wettest area with an average annual wet-day rainfall of more than 2200 mm is on the western coast of Myanmar, whereas the driest region is located in the center of the Indochina Peninsula, including northern Myanmar, northern Thailand and northern Laos. The mean climatology of very wet days (R95p) and extremely wet days (R99p) (Figure 4d,e) show that the lowest intensity R95p index is at the point as the lowest intensity of the R99p index, which are at the point of 95.25–21.25 with 111 mm for the R95p index and 34 mm for the R99p index. The highest intensity is 771 mm for the R95p index, which is at the point of 92.25–21.25 and 261 mm for the R99p index is at the point of 103.25–5.25. It can be inferred from these two indices that the regions with high rainfall intensity are situated in four places around the eastern coast of northern Vietnam, the eastern coast of southern Thailand and the western coast of Myanmar, whereas other regions have medium and low rainfall intensities.

The Simple Daily Intensity Index (SDII) (Figure 4f) ranges from 4 mm/day at 95.25–21.25 to 20 mm/day at 93.25–20.25. The pattern is similar to the R20mm index and the R25mm index, and the maximum value is found on the coast of northern Myanmar, whereas other places are dominated by medium to low intensities, including parts of Thailand, Cambodia, Laos, Vietnam, and northern Myanmar.

3.2. Temporal Trend of Extreme Rainfall Indices

Analysis is completed to identify the possible temporal changes of the frequency and intensity of extreme rainfall events over the Indochina Peninsula. Trends in extreme rainfall indices were calculated using statistical software, RClimDex, an R-based language program. The positive (negative) values indicate increasing (decreasing) trends. This study used a significance level α of 5%. The slope represents the magnitude of the changes each year, such as day/year for the frequency indices and mm/year for the intensity indices.

Trends in indices were calculated using the Mann-Kendall test. Positive or the negative trends could be identified using the Z test. This calculation also produced the p-Value. The p-Value was compared with α = 5% (0.05), where if the p-Value was less (greater) than α, then the trend was categorized as significant (non-significant).

3.2.1. Frequency Indices

The consecutive dry days (CDD) index shows non-significant trends dominated this area. A total of 215 out of 248 grids show non-significant trends, with 65.72% of the grids indicating positive trends and 20.96% indicating negative trends (see Table 2). The remaining 32 grids demonstrate significant trends with 10.88% of the grids indicating positive trends and 2.41% indicating negative trends. Figure 5 shows the most significant positive and negative trends of the CDD index. The most significant positive trend is at 105.25–17.25 with a slope of 1117, while the most significant negative trend is at 107.25–10.25 with a slope of −0.853 [1].

In contrast to the consecutive dry days (CDD), the consecutive wet day (CWD) results indicate 194 grids show non-significant trends with 36.29% of the grids indicating positive trends and 41.93% indicating negative trends (see Table 2). The remaining 53 grids demonstrate significant trends with 6.85% of grids indicating positive trends and 14.51% indicating negative trends. Figure 6 indicates the most significant negative and positive trends. The most significant positive trend is at 104.25–18.25 with a slope of 1.1588, while the most significant negative trend is found at 95.25–16.25 with a slope of −1.488 [1].

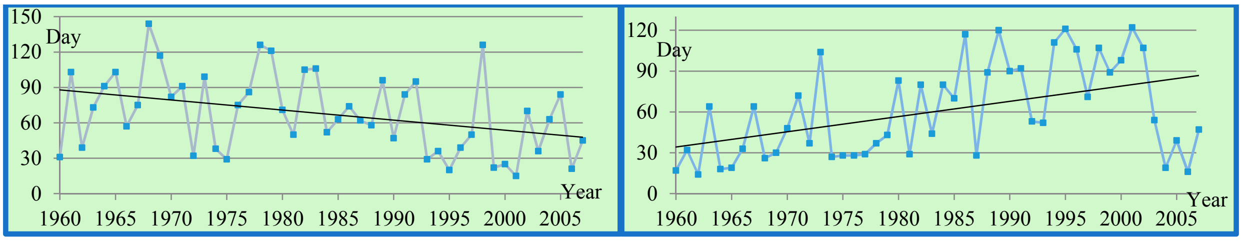


Figure 5. The most significant negative trend with a slope of −0.8531 (**left**) and the most significant positive trend with a slope of 1.1178 (**right**) of the CDD index.

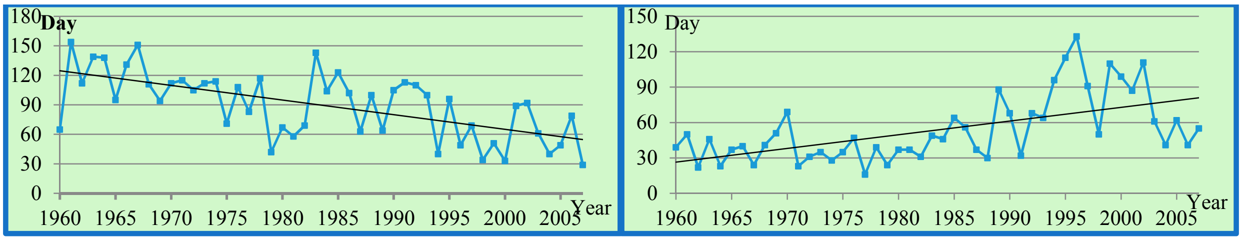


Figure 6. The most significant negative trend with a slope of −1.4889 (**left**) and the most significant positive trend with a slope of 1.1588 (**right**) of the CWD index.

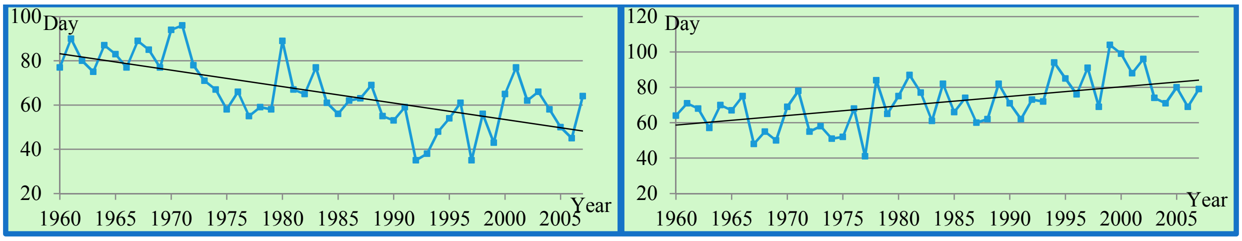


Figure 7. The most significant negative trend with a slope of −0.7432 (**left**) and the most significant positive trend with a slope of 0.5404 (**right**) of the R10mm index.

Heavy rainfall day (R10mm), very heavy rainfall day (R20mm) and extremely heavy rainfall day (R25mm) indices show non-significant trends still dominate in the Indochina Peninsula with 187 grids for the R10mm index, 183 grids for the R20mm index, and 178 grids for the R25mm index. The areas that experience the most significant positive trends are at 103.25–18.25 for the R10mm index with a slope of 0.54, at 90.25–22.25 for the R20mm index with a slope of 0.2942, and at 109.25–13.25 for the R25mm index with a slope of 0.231. Otherwise, the areas that experience the most significant negative trends are at 93.25–8.25 for the R10mm index with a slope of −0.743, at 93.25–8.25 for the R20mm index with a slope of −0.4493, and at 94.25–18.25 for the R25mm index with a slope of −0.380 (See Figures 7–9).

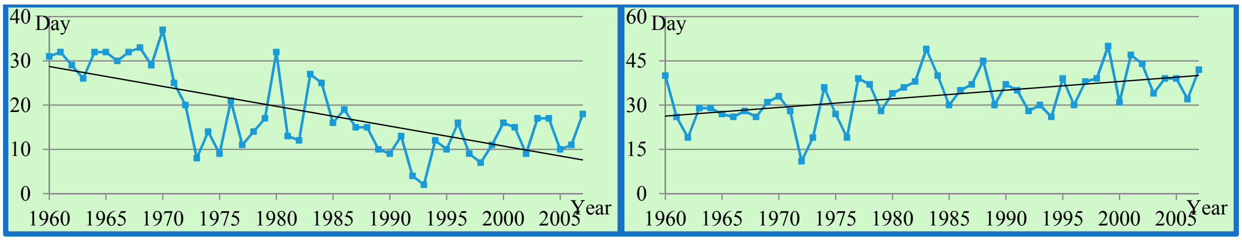


Figure 8. The most significant negative trend with a slope of −0.4493 (**left**) and the most significant positive trend with a slope of 0.2942 (**right**) of the R20mm index.

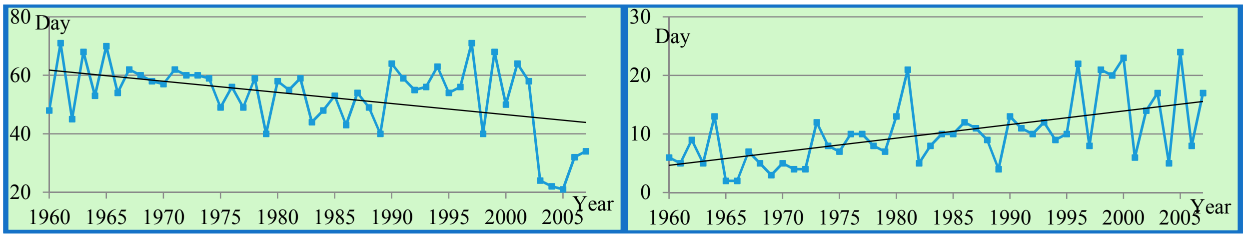


Figure 9. The most significant negative trend with a slope of −0.3809 (**left**) and the most significant positive trend with a slope of 0.2318 (**right**) of the R25mm index.

Table 2. The percentage of significant and non-significant trends of frequency indices.

Indices	Positive Significant Trend (%)	Positive Non-Significant Trend (%)	Negative Significant Trend (%)	Negative Non-Significant Trend (%)
CDD	10.88	65.72	2.41	20.96
CWD	6.85	36.29	14.51	41.93
R10mm	11.69	39.11	12.5	36.29
R20mm	17.33	37.5	8.46	36.29
R25mm	20.96	36.29	6.85	35.08

3.2.2. Intensity Indices

The daily maximum rainfall (RX1day) index shows the highest amount of rainfall in a single day of each year. From the simulation results, 12 grids show significant negative trends with the most significant trends at 93.25–8.25 with a slope of −0.67, and 49 grids show significant positive trends with the most significant trend at 96.25–4.25 with a slope of 1.111. Otherwise, 79 grids indicate non-significant negative trends, and 105 grids show non-significant positive trends (Figure 10).

In the five-day maximum rainfall (RX5day) index simulation result, 207 grids show non-significant trends, and 39 grids show significant trends. The most significant negative trend is at 94.25–24.25 with a slope of −1.3859, and the most significant positive trend is at 91.25–22.25 with a slope of 2.2312 (Figure 11).

In the annual wet-day rainfall total (PRCPTOT) index, 66 grids show significant trends, and 181 grids show non-significant trends, where 12.5% of grids show significant positive trends, 33.46% show non-significant positive trends, 14.11% show significant negative trends, and 39.51% show non-significant negative trends (see Table 3). The most significant positive trend is at 109.25–13.25 with a slope of 16.367, and the most significant negative trend is found at 93.25–8.25 with a slope of −16.178 (Figure 12).

From the very wet day (R95p) and extremely wet day (R99p) indices, the R95p index demonstrates that 74 grids show significant trends and 173 grids show non-significant trends. The most significant positive trend is at 109.25–13.25 with a slope of 11.127, and the most significant negative trend is at 93.25–8.25 with a slope of −12.822 (Figure 13). The simulation result of the R99p index shows that 68 grids indicate significant trends, and 179 grids indicate non-significant trends. The most significant positive trend of the R99p index is at 91.25–22.25 with a slope of 7.309, and the most significant negative trend is at 93.25–825 with a slope of −6.3959 (Figure 14).

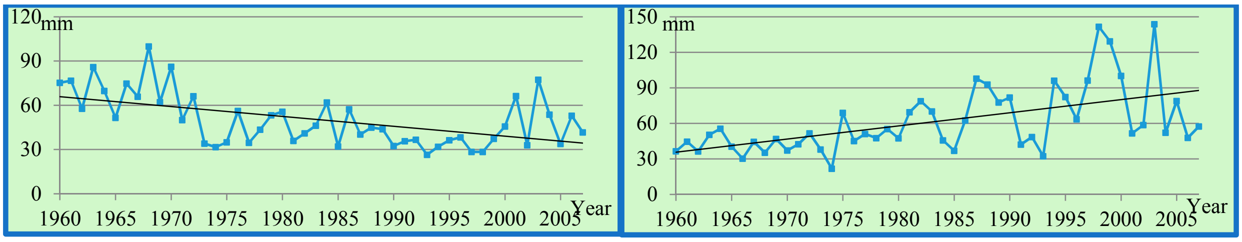


Figure 10. The most significant negative trend with a slope of −0.6701 (**left**) and the most significant positive trend with a slope of 0.1116 (**right**) of the RX1day index.

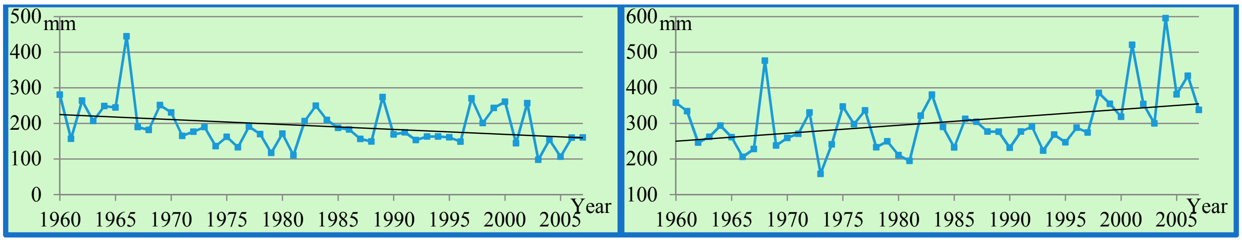


Figure 11. The most significant negative trend with a slope of −1.3859 (**left**) and the most significant positive trend with a slope of 2.2312 (**right**) of the RX5day index.

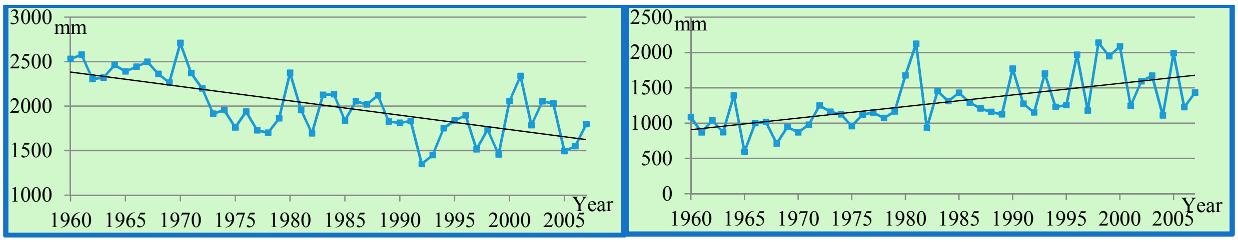


Figure 12. The most significant negative trend with a slope of −16.178 (**left**) and the most significant positive trend with a slope of 16.367 (**right**) of the PRCPTOT index.

The Simple Daily Intensity Index (SDII) index is the ratio between the annual wet-day rainfall total and the total number of rainy days. There are 68 grids form the 248 grids that experience significant trends, and the remaining 179 grids experience non-significant trends, where 17.74% of grids show significant positive trends, 40.72% show non-significant positive trends, 9.67% show significant negative trends, and 31.45% show non-significant negative trends (see Table 3). The most significant positive trend is at 90.25–22.25 with a slope of 0.0903, and the most significant negative trend is found at 93.25–8.25 with a slope of −0.0681 (Figure 15). Table 3 is a summary of the percentage of intensity indices in the study area.

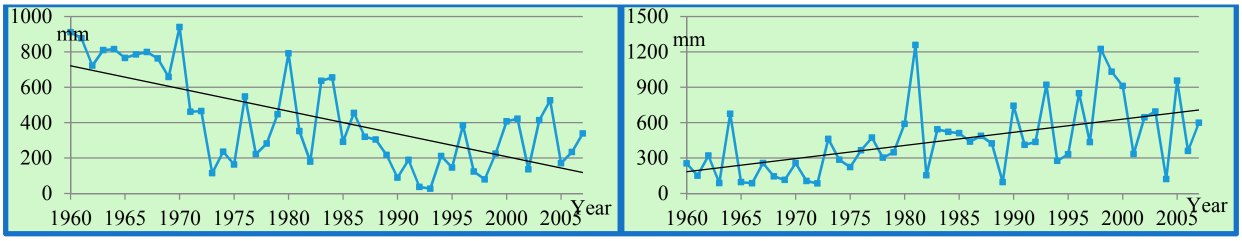


Figure 13. The most significant negative trend with a slope of −12.822 (**left**) and the most significant positive trend with a slope of 11.127 (**right**) of the R95p index.

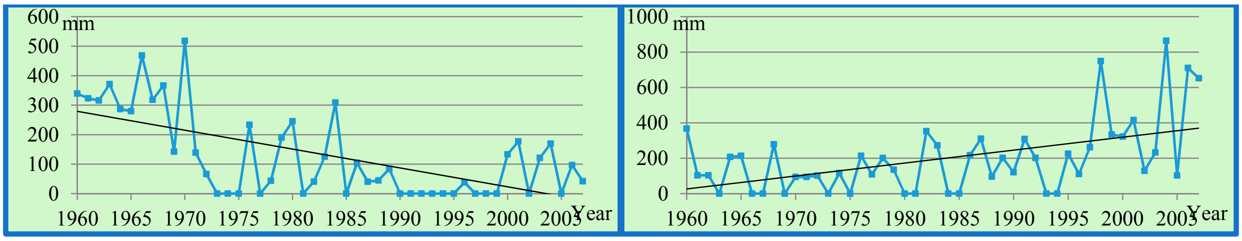


Figure 14. The most significant negative trend with a slope of −6.3959 (**left**) and the most significant positive trend with a slope of 7.3096 (**right**) of the R99p index.

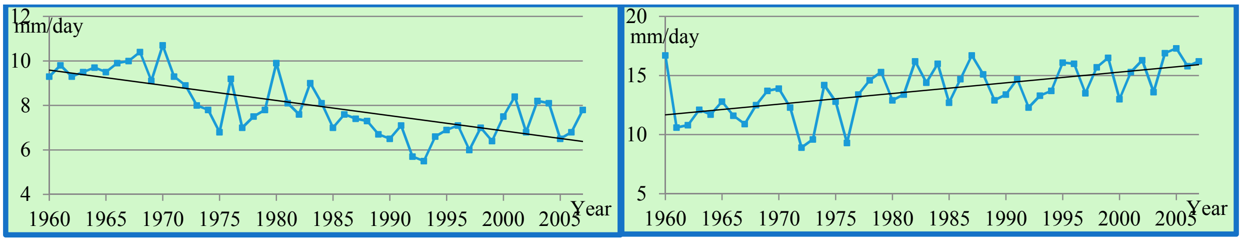


Figure 15. The most significant negative trend with a slope of −0.0681 (**left**) and the most significant positive trend with a slope of 0.0903 (**right**) of the SDII index.

Table 3. Percentage of significant and non-significant trends of intensity indices.

Indices	Positive Significant Trend (%)	Positive Non Significant Trend (%)	Negative Significant Trend (%)	Negative Non Significant Trend (%)
RX1day	20.16	42.74	4.83	31.85
RX5day	24.19	37.9	5.64	31.85
PRCPTOT	12.5	33.46	14.11	39.51
SDII	17.74	40.72	9.67	31.45
R95p	24.19	37.90	5.64	31.85
R99p	22.17	39.91	5.24	32.25

Because the population of the Indochina Peninsula countries (Vietnam, Thailand, Myanmar, Cambodia, Laos, and some parts of Malaysia, China, Bangladesh, and India) total nearly 250 million people, the Indochina Peninsula is a center of southeastern Asia economic activities. Therefore, the analysis of extreme rainfall events in this area is very important because extreme rainfall results in several disasters, such as floods and landslides, affecting human activity.

A majority of the Indochina Peninsula residents live in the major cities, such as Bangkok, Phnom Penh, Saigon, Hanoi, Vientiane, and Yangon. Additionally, these cities are the administrative center of southeastern Asian countries, the center of economic development, industrialization, and infrastructure establishment. Thus, extreme rainfall analysis is imperative in this area.

Tables 4–6 explain the extreme rainfall indices through the major cities over the Indochina Peninsula, including Bangkok, Phnom Penh, Saigon, Hanoi, Vientiane, and Yangon. Hanoi experiences a negative trend in most indices, except Consecutive Wet Days (CWD) index, while Phnom Penh experiences positive trends in all indices. All other cities experience both positive and negative trends evenly.

Impacts resulting from extreme rainfall events, such as floods, landslides, droughts, and other related disasters, are associated with increasing urbanization, industrialization, infrastructures and economic development in the Indochina Peninsula countries and can be anticipated.

Table 4. The trends of frequency indices close to major cities in the Indochina Peninsula.

No	Lat	Lon	Near City	R10mm	R20mm	R25mm	CDD	CWD
				Days	Days	Days	Days	Days
1	100.25	14.25	Bangkok	−0.103	−0.003	−0.009	0.599	−0.096
2	104.25	11.25	Phnom Penh	0.041	0.058	0.05	0.404	0.291
3	105.25	21.25	Hanoi	−0.091	−0.051	−0.005	−0.062	0.054
4	106.25	10.25	Saigon	0.277	0.084	0.029	−0.578	0.36
5	102.25	17.25	Vientiane	0.012	−0.021	−0.013	0.184	0.204
6	96.25	16.25	Yangon	−0.059	−0.056	0.067	0.363	−0.897

Table 5. The trends of intensity indices close to major cities in Indochina.

No	Lat	Lon	Near City	RX1 Day	RX5 Day	PRCPTOT
				mm	mm	Mm
1	100.25	13.25	Bangkok	0.181	0.074	−2.353
2	104.25	11.25	Phnom Penh	0.135	0.4	0.475
3	105.25	21.25	Hanoi	−0.363	−0.357	−2.154
4	106.25	10.25	Saigon	0.133	0.413	7.602
5	102.25	17.25	Vientiane	−0.208	−0.021	0.505
6	96.25	16.25	Yangon	0.4	0.802	1.587

Table 6. The trends of intensity indices close to major cities in Indochina (Continued).

No	Lat	Lon	Near City	SDII	R95p	R99p
				mm/day	mm	Mm
1	100.25	13.25	Bangkok	0.003	0.411	−0.587
2	104.25	11.25	Phnom Penh	0.011	1.819	1.453
3	105.25	21.25	Hanoi	−0.015	−1.176	−0.663
4	106.25	10.25	Saigon	0.017	2.517	1.096
5	102.25	17.25	Vientiane	−0.01	−1.209	−1.314
6	96.25	16.25	Yangon	0.017	4.269	2.841

Tables 4–6 conclude the precipitation trends close to the major cities in the Indochina Peninsula, where Hanoi and Saigon are located in the eastern area of the Indochina Peninsula, Vientiane and Phnom Penh are located in the central are of the Indochina Peninsula, and Bangkok and Yangon are located in the western area of the Indochina Peninsula.

Hanoi and Saigon experience negative trends in the CCD index as it is influenced by the two cities being located in the coastal area facing to the Pacific Ocean and by the northeastern monsoon, which occurs every October until March. Yangon and Bangkok experience positive trends in contrast to those in the eastern area of the Indochina Peninsula and are influenced strongly by the southwestern monsoon, which occurs every May until September. Meanwhile, the two cities in the central area of the Indochina Peninsula, Vientiane and Phnom Penh, experience positive trends but with a lower slope.

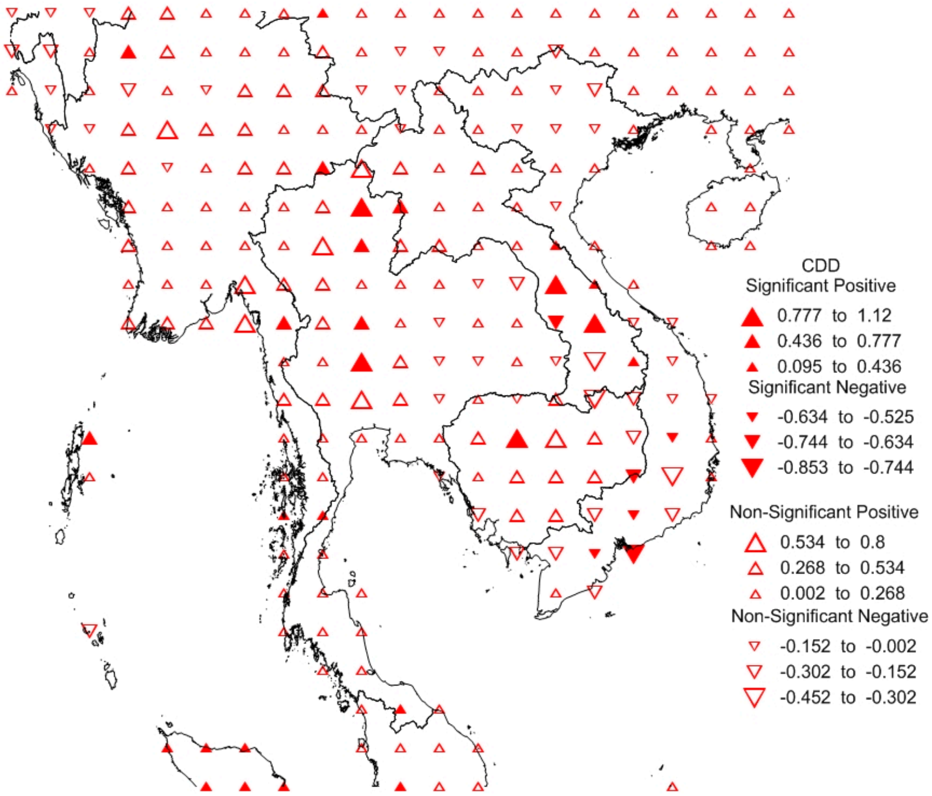
The opposite pattern is shown from the CDD index, of which Hanoi and Saigon experience positive trends, Yangon and Bangkok experience negative trends, Vientiane and Phnom Penh experience negative trends. Hanoi experiences a negative trend in most indices except the CWD index, while Saigon experiences a positive trend in most indices, except CDD index, despite the two cities being located in the eastern area of the Indochina Peninsula. This difference is because Hanoi is located in the northern Vietnam, whereas Saigon is located in southern Vietnam and is influenced by the northeastern and southwestern monsoons, which occur successively every year. Meanwhile, the remaining indices occur randomly between positive (negative) significant (non-significant) trends.

3.3. Spatial Pattern of Detected Trend

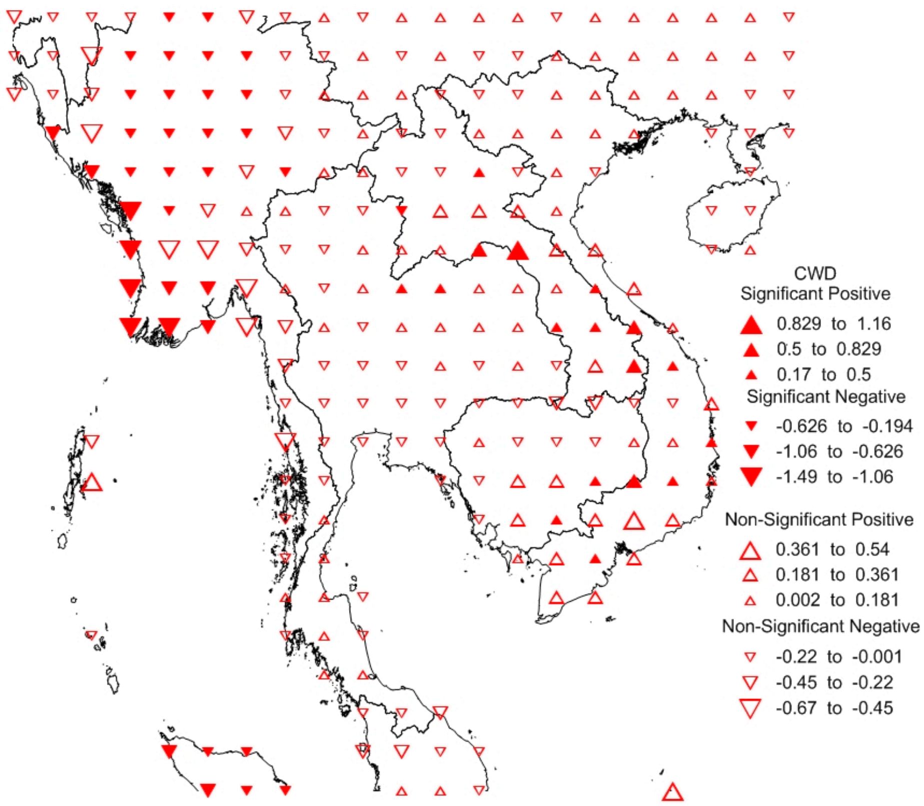
The purposes of the spatial patterns analysis of extreme rainfall trends are to describe the distribution of data in geographic space, measure the spatial relationship and identify the spatial pattern where areas experience positive (negative) significant (non-significant) trends, whether the resulting in a random, spread, or other particular pattern. This study used a point pattern analysis by plotting each grid onto the Indochina Peninsula Map. Hence, areas that have the potential for extreme rainfall events can be seen, and early preventive actions can be initiated.

3.3.1. Frequency Indices

The spatial patterns of consecutive dry day (CDD) and consecutive wet day (CWD) indices are shown in Figure 16a,b, respectively. A majority of the eastern coast of the Indochina Peninsula, including the eastern coasts of Vietnam and southern Thailand, experience negative, and at times significant, trends for the CDD index. A contrasting pattern occurs on the western coast of the Indochina Peninsula, where most grids experience positive trends, significant at times. Meanwhile, for CWD index, positive trends occur in the eastern region of the Indochina Peninsula along the eastern coasts of Vietnam and southern Thailand, where some grid trends are significant. In contrast, western coast of the Indochina Peninsula shows negative trends, significant at times [1].

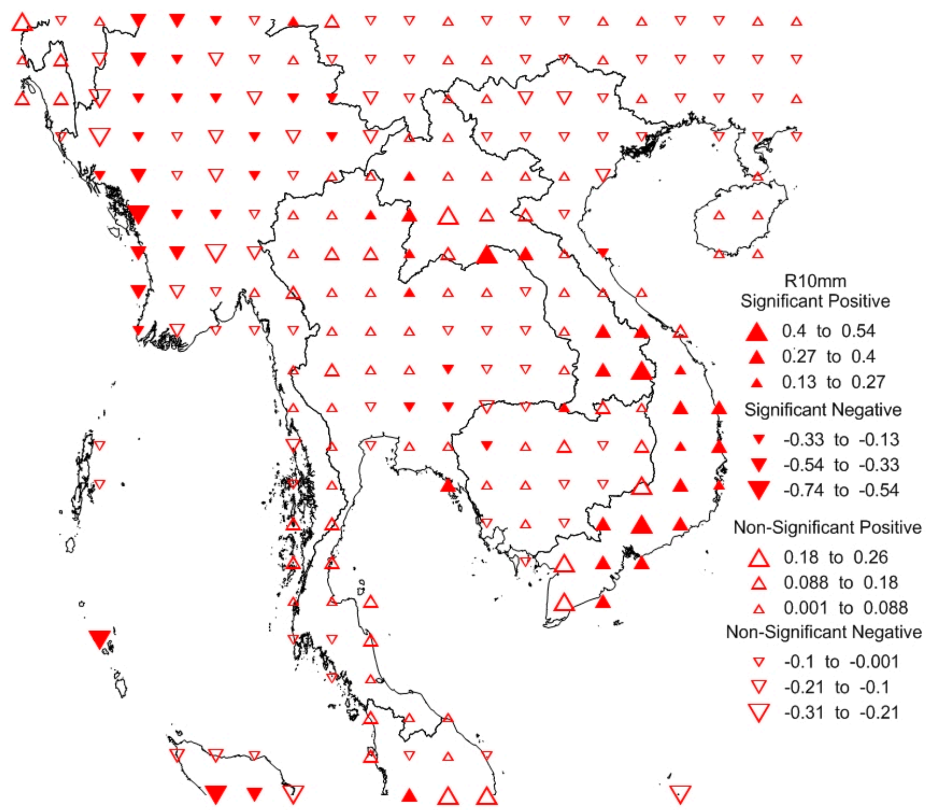


(**a**)

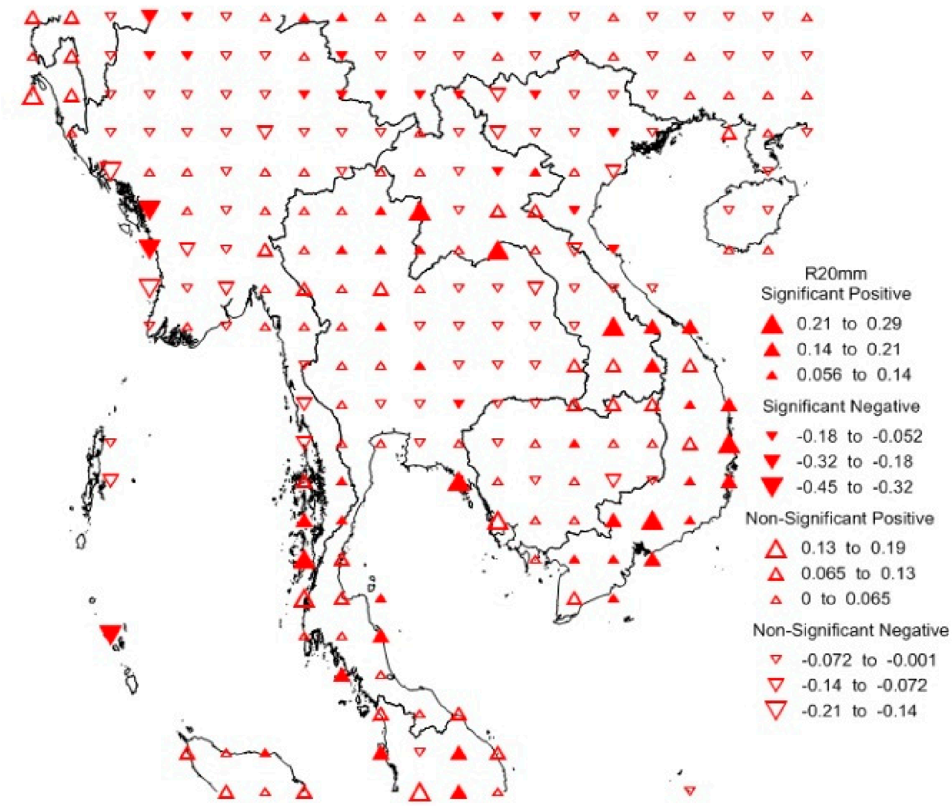


(**b**)

Figure 16. *Cont.*

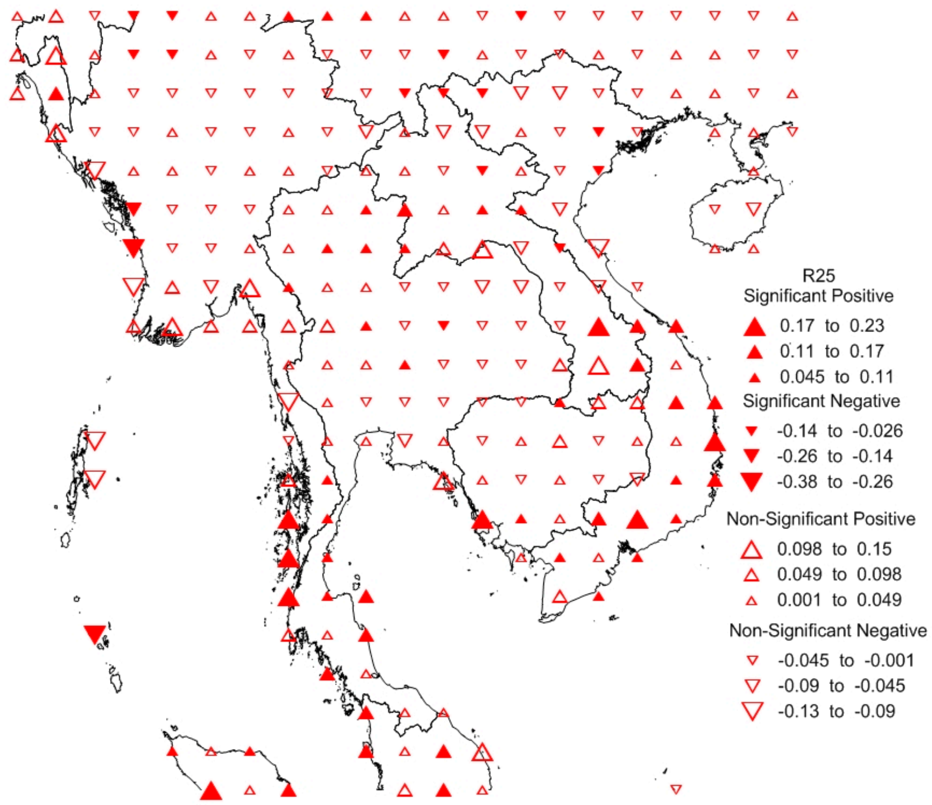


(**c**)



(**d**)

Figure 16. *Cont.*



(**e**)

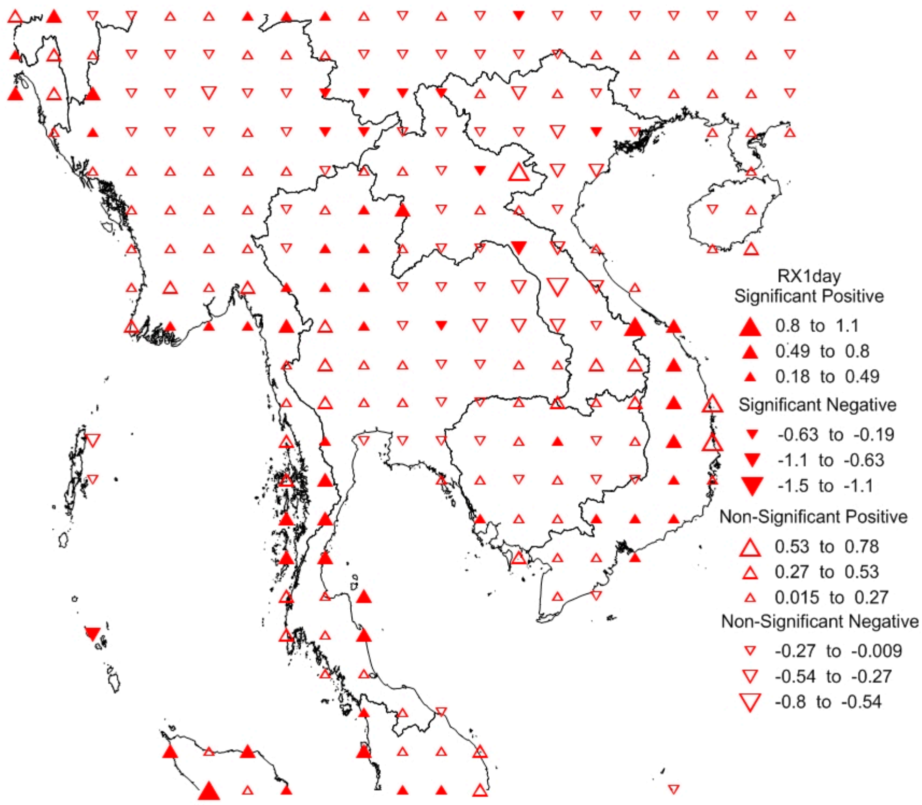
Figure 16. The point pattern analysis of frequency indices of extreme rainfall over the Indochina Peninsula. (**a**) CDD; (**b**) CWD; (**c**) R10mm; (**d**) R20mm; (**e**) R25mm.

The indices of heavy rainfall days (R10mm), very heavy rainfall days (R20mm), and extremely heavy rainfall days (R25mm) indicate a similar pattern (Figure 16c–e). Many positive trends are found along the eastern coast of the Indochina Peninsula, the coast of Vietnam and the coast of southern Thailand (Gulf of Thailand), all of which face to the Pacific Ocean, where some grids contain significant trends. The negative trends are found primarily in Myanmar and along the western coast of the Indochina Peninsula (Andaman Sea) facing the Indian Ocean with several grids indicating significant trends.

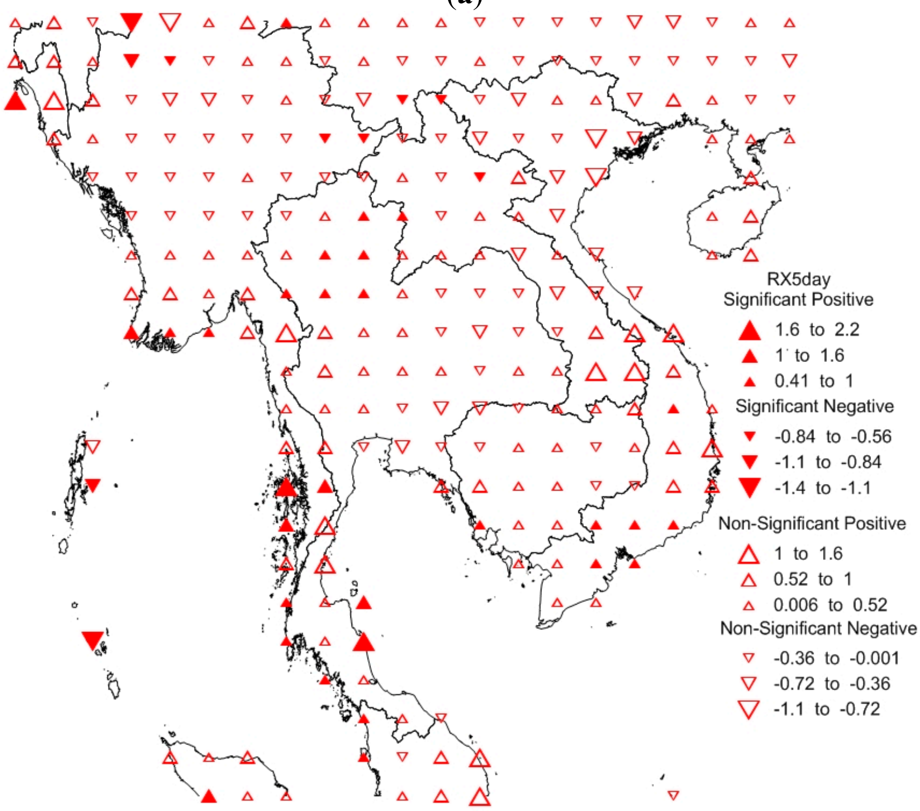
3.3.2. Intensity Indices

The spatial pattern of the daily maximum rainfall (RX1day) and 5-day maximum rainfall (RX5day) indices are shown in Figure 17a,b, respectively, where the spread in positive trends is large in most parts of the Indochina Peninsula with a variety of trends. Some patterns of negative trends are also found in several places, such as in a small area in northern Myanmar, most of Laos, northern Vietnam and southern China Mainland.

The spatial pattern analysis of the annual wet-day rainfall total (PRCPTOT) index in Figure 17c shows a contrasting pattern between the southeastern and northwestern areas of the Indochina Peninsula. The southeastern area of the Peninsula is dominated by significant positive trends, whereas the northwestern area of the Indochina Peninsula is dominated by significant negative trends. Whereas other areas, such as southern China, experience non-significant negative trends, other regions experience a spread pattern that is distributed evenly between positive and negative trends.

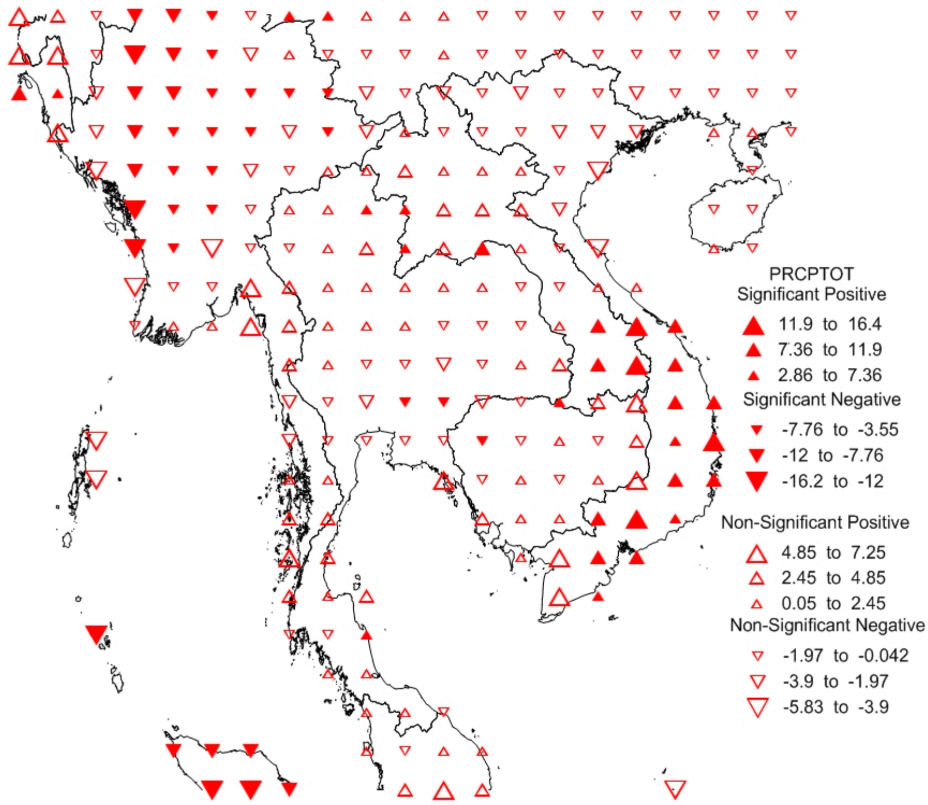


(**a**)

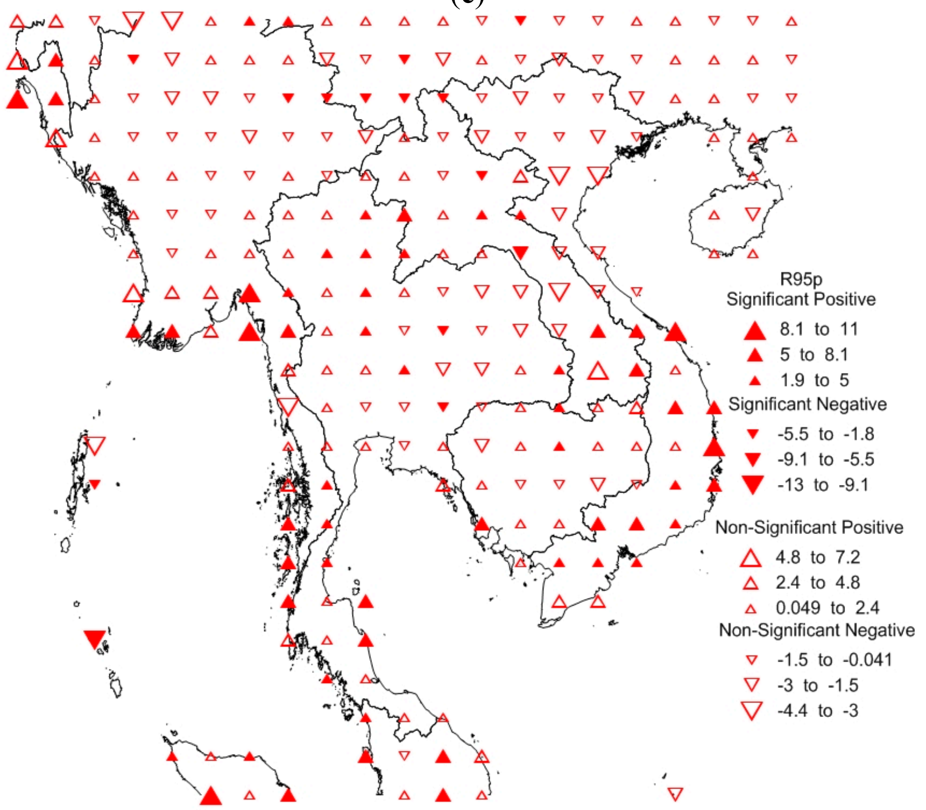


(**b**)

Figure 17. *Cont.*

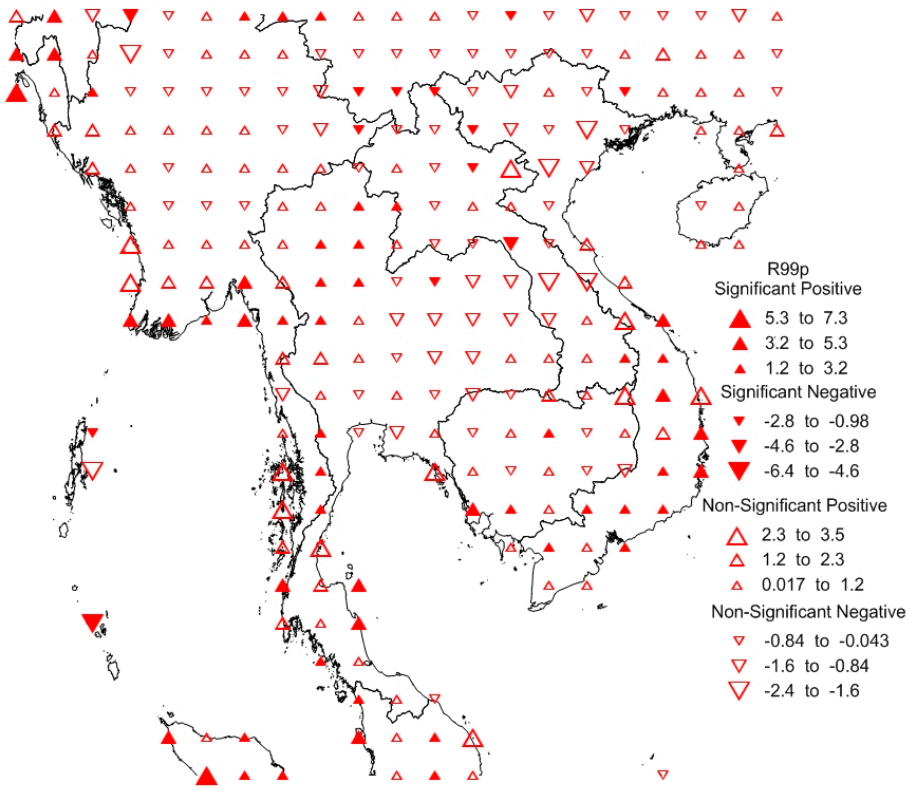


(**c**)

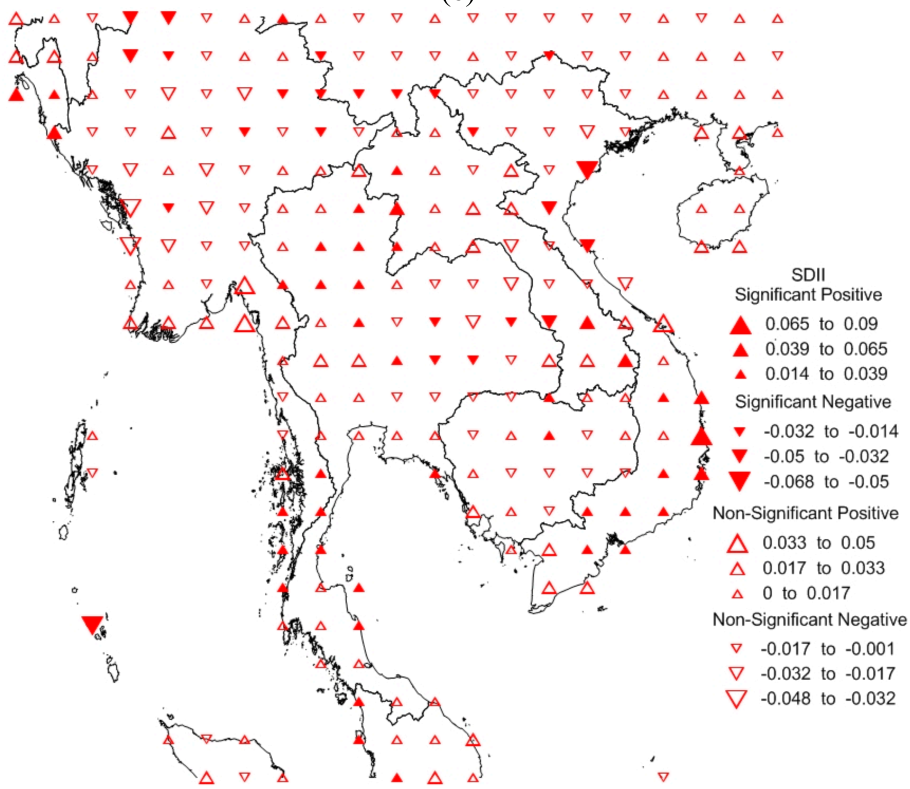


(d)

Figure 17. *Cont.*



(**e**)



(**f**)

Figure 17. The point pattern analysis of intensity indices of extreme rainfall over the Indochina Peninsula. (**a**) RX1day; (**b**) RX5day; (**c**) PRCPTOT; (**d**) R95p; (**e**) R99p; (**f**) SDII.

Very wet day (R95p) and extremely wet day (R99p) indices (see Figure 17d,e) show the random patterns of positive (negative) significant (non-significant) trends. The Simple Daily Intensity Index (SDII) indicates that positive trends dominate the southeastern part of the Indochina Peninsula and southern Thailand with some grids showing significant trends (see Figure 17f).

4. Conclusions

The pattern of the mean climatology of each index can be described. All extreme indices, including frequency and intensity, have similar patterns and specific geographic locations in the Indochina Peninsula. The highest intensity of mean climatology is situated primarily on the northern coast of Myanmar, northern Vietnam, and southern Thailand (border with Malaysia). Other regions have a mean climatology that ranges from medium to low intensity, which dominates the central area of the Indochina Peninsula.

This study also found that the Indochina Peninsula is dominated by non-significant trends that spread evenly across the Indochina Peninsula with the percentage of respective positive and negative significant trends of 11.69 and 12.5% for the R10mm index, 17.33 and 8.46% for the R20mm index, 20.96 and 6.85% for the R25mm index, 10.88 and 2.41% for the CDD index, 6.85 and 14.51% for the CWD index, 20.16 and 4.83% for the RX1day index, 24.29 and 5.64% for the RX5day index, 12.5 and 14.11% for the PRCPTOT index, 17 and 9.67% for the SDII index, 24.5 and 5.64% for the R95p index, and 22.17 and 5.24% for the R99p index.

The CDD and CWD indices show contrasting trends between the western and eastern areas of the Indochina Peninsula. Most of the eastern coast of the Indochina Peninsula, including the eastern coasts of Vietnam and Thailand, experience negative trends in the CDD index with some grids indicating significant trends. Additionally, negative trends in the CWD index occur on the western coast of the Indochina Peninsula with some grids showing significant trends.

The R10mm, R20mm, and R25mm indices have similar patterns where many positive trends are found on the eastern coast of the Indochina Peninsula, along the coast of Vietnam and along the coast of southern Thailand (Gulf of Thailand), all of which face the Pacific Ocean, with some grids show significant trends. Meanwhile, negative trends are found in most areas of Myanmar and along the western coast of the Indochina Peninsula (Andaman Sea), both of which face the Indian Ocean, with several grids show significant trends.

The distribution of positive trends in the RX1day and RX5day indices are spread in most areas of the Indochina Peninsula with a variety of trend levels, and most grids show significant trends. Some patterns of negative trends are found in several places, such as in a small area of northern Myanmar, most of Laos, northern Vietnam and southern China Mainland.

The PRCPTOT index shows a contrasting pattern between the southeastern and northwestern Indochina Peninsula. The southeastern area of the Indochina Peninsula is dominated by significant positive trends, whereas the northwestern region of the Indochina Peninsula is dominated by significant negative trends. In other regions, such as southern China, experience non-significant negative trends.

The R95p and R99p indices were obtained with a random pattern of positive (negative) significant (non-significant) trends that spread evenly across the countries. Meanwhile, the SDII index shows that positive trends dominate the southeastern part of the Indochina Peninsula and southern Thailand with some grids showing significant trends.

Acknowledgments

The authors would like to thank the Mathematics Department of King Mongkut's University of Technology Thonburi (KMUTT), Bangkok, Thailand for research funding. Acknowledgements are also given to East Kalimantan Government of Indonesia through Kaltim Cemerlang for the scholarship during studying at KMUTT.

Author Contributions

Muhammad Yazid: Conceptualization, data collection, quality control and data analysis, wrote the paper, revised, and finalized the manuscript. Usa Humphries: Conceptualization, quality control, data analysis, revised the manuscript with direct input of writing and comments.

Conflicts of Interest

The authors declare no conflicts of interest.

References

1. Yazid, M.; Humphries, U.; Sudarmadji, T. Spatiotemporal of extreme rainfall events in the Indochina peninsula. In Proceedings of the 2014 International Conference on Applied Statistics, Khon Kaen, Thailand, 21–24 May 2014; pp. 238–245.
2. Abbas, F.; Ahmad, A.; Safeeq, M.; Ali, S.; Saleem, F.; Hammad, H.M.; Farhad, W. Changes in precipitation extremes over arid to semiarid and subhumid punjab, Pakistan. *J. Theor. Appl. Climatol.* **2013**, doi:10.1007/s00704-013-0988-8.
3. Atsamon, L.; Sangchan, L.; Thavivongse, S. Assessment of extreme weather events along the coastal areas of Thailand. In Proceedings of the 2009 Conference on Climate Variability and Change, Washington, DC, USA, 2–6 February 2009.
4. Klein Tank, A.M.G.; Konnen, G.P. Trends in indices of daily temperature and precipitation extremes in Europe, 1946–1999. *J. Clim.* **2003**, *16*, 3665–3680.
5. Santos, C.A.C.; Brito, J.I.B.; Junior, C.H.F.S.; Dantas, L.G. Trends in precipitation extremes over the northern part of Brazil from Era40 dataset. *Rev. Bras. Geogr. Fis.* **2012**, *4*, 836–851.
6. Kunkel, K.E.; Andsager, K.; Easterling, D.R. Long-term trends in extreme precipitation events over the conterminous United States and Canada. *J. Clim*. **1999**, *12*, 2515–2527.
7. Mason, S.J.; Waylen, P.R.; Mimmack, G.M.; Rajaratnam, B.; Harrison, J.M. Changes in extreme rainfall events in South Africa. *Clim. Chang.* **1999**, *41*, 249–257.
8. Haylock, M.; Nicholls, N. Trends in extreme rainfall indices for an updated high quality data set for Australia, 1910–1998. *Int. J. Climatol.* **2000**, *20*, 1533–1541.
9. Suppiah, R.; Hennessy, K.J. Trend in total rainfall, heavy rain events and number of dry days in Australia, 1910–1990. *Int. J. Climatol.* **1998**, *10*, 1141–1164.
10. Fu, G.; Viney, N.R.; Charles, S.P.; Liu, J. Long-term temporal variation of extreme rainfall events in Australia: 1910–2006. *J. Clim.* **2010**, *11*, 950–965.

11. Choi, G.; Collins, D.; Ren, G.; Trewin, B.; Baldi, M.; Fukuda, Y.; Afzaal, M; Pianmana, T.; Gomboluudev, P.; Huong, P.T. Changes in means and extreme events of temperature and precipitation in the Asia-Pacific Network region, 1955–2007. *Int. J. Climatol.* **2009**, *29*, 1906–1925.
12. Yin, H.; Donat, M.G.; Alexander, L.V.; Sun, Ying. Multi-dataset comparison of gridded observed temperature and precipitation extremes over China. *Int. J. Climatol.* **2014,** doi:10.1002/joc.4174
13. Tank, A.M.G.K.; Zwiers, F.W.; Zhang, X. Guidelines on analysis of extremes in a changing climate in support of informed decisions for adaptation. In *Climate Data and Monitoring*; World Meteorological Organization: Geneva, Switzerland, **2009**, pp.50–52.
14. Jones, C.; Waliser, D.E.; Lau, K.M.; Stern, W. Global occurrences of extreme precipitation and the Madden—Julian Oscillation: Observations and predictability. *J. Clim.* **2004**, *17*, 4575–4589.
15. Salomon, S.; Qin, D.; Manning, M.; Chen, Z.; Marquis, M.; Averyt, K.B.; Tignor, M.; Miller, H.L. *Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)*; Cambridge University Press: Cambridge, UK, 2007.
16. Carvalho, L.M.V.; Jones, C.; Liebmann, B. Extreme precipitation events in southeastern south America and large-scale convective patterns in the south Atlantic convergence zone. *J. Clim.* **2002**, *15*, 2377–2394.
17. Testik, F.Y.; Gebrenichael, M. *Rainfall: State of the Science*; American Geophysical Union: Washington, DC, USA, 2013.
18. Frei, C.; Schar, C. Detection probability of trends in rare event: Theory and application to heavy precipitation in the alpine region. *J. Clim.* **2000**, *14*, 1568–1584.
19. Yatagai, A.; Kamighuci, K.; Arakawa, O.; Hamada, A.; Yasutomi, N.; Kitoh, A. Aphrodite constructing a long-term daily gridded precipitation dataset for asia based on a dense network of rain gauges. *Am. Meteorol. Soc.* **2012**, 1401–1415.
20. Hamada, A.; Arakawa, O.; Yatagai, A. An automated quality control method for daily rain-gauge data. *Global Environ. Res.* **2011**, *15*, 183–192.
21. Zhang, X.; Alexander, L.; Hegerl, G.C.; Jones, P.; Klein, T.A.; Peterson, T.C.; Trewin, B.; Zwier, F.W. Indices for monitoring changes in extremes based on daily temperature and precipitation data. *Clim. Chang.* **2011**, doi:1002/wcc.147.
22. Zhang, X.; Hogg, W.D.; Mekis, E. Spatial and temporal characteristics of heavy precipitation events over Canada. *Am. Meteorol. Soc.* **2001**, *14*, 1923–1936.
23. Subyani, A.M. Geostatistical study of annual and seasonal mean rainfall pattern in southwest Saudi Arabia. *J. Meteorol. Sci.* **2004**, *49*, 803–817.