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Rainfall extremes in Northern Vietnam: a comprehensive analysis of patterns and trends

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ABSTRACT

This study examines the characteristics and trends of extreme rainfall in Northern Vietnam from 1961 to 2018, using daily rainfall data collected from 37 meteorological stations. The study reveals that the average annual rainfall varies significantly across stations, ranging from 1140 mm to 4758 mm. The rainy season accounts for 73% to 92% of the total annual rainfall. Most stations show a declining trend in the annual total rainfall during wet days (PRCPTOT) and the number of wet days (WDAY), while rainfall intensity (SDII) has increased in most stations, particularly during the dry season. This can be attributed to an increase in PRCPTOT and a decrease in WDAY in the dry season. The study also finds a general decreasing trend in the annual maximum 1-day precipitation (RX1day) and consecutive 5-day precipitation (RX5day), as well as for the number of moderate (R16mm) and heavy (R50mm) rainfall days. However, most stations in Northern Vietnam demonstrate no trend in the annual maximum number of consecutive dry days (CDD) and the annual maximum number of consecutive wet days (CWD). Furthermore, the frequency of extreme rainfall events in Northern Vietnam exceeding the 5-year and 10-year return values of 1961-2018 has decreased in recent decades at many stations. Overall, the findings of this study provide insights into the changing patterns of extreme rainfall in Northern Vietnam, with significant implications for climate change adaptation and disaster risk reduction efforts in the region.

Keywords: Climate change, rainy season, extreme rainfall, generalized extreme distribution, trend analysis, Northern Vietnam.

1. Introduction

Global warming has been identified as a key factor in altering the frequency, intensity, spatial extent, and timing of extreme events, ultimately leading to the emergence of unprecedented rainfall extremes (IPCC, 2021). Numerous studies have demonstrated that extreme precipitation, such as annual maximum 1-day precipitation (RX1day), annual maximum consecutive 5-day precipitation (RX5day), and daily mean precipitation intensities, have increased across many regions over land in recent decades (Donat et al., 2016; Du et al., 2019; Dunn et al., 2020; Sun et al., 2021). Most countries in Southeast Asia have also witnessed an increase in rainfall intensity along with a downward trend in wet days (Cheong et al., 2018; Endo et al., 2009; Limsakul et al., 2016; Supari et al., 2017). Besides, Villafuerte et al. (2015) found that RX1day declined over much of the Maritime Continent between 1951-2007.

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In Vietnam, a country heavily affected by climate change (Espagne et al., 2021), numerous studies have been conducted to investigate observed rainfall characteristics and trends. Based on data collected from a limited number of rain gauge stations between the 1950s and early 2000s, analyses indicated an increase in rainfall in the south of Vietnam and a decrease in the north (Manton et al. 2001; Endo et al. 2009; MONRE 2009; Ngo-Duc and Phan-Van 2012). MONRE (2012) updated the results of MONRE (2009) and demonstrated that RX1day and the number of heavy rain days tended to increase across most climatic sub-regions. MONRE (2016) and MONRE (2020) updated data for 150 meteorological stations in Vietnam through 2014 and 2018, respectively, and added analysis of past seasonal trends.

It should be noted, however, that the above analysis results are typically analyzed for the spatial avarge of a climatic sub-region, or only for a small number of stations in Vietnam. Additionally, the length of the rainfall data series at monitoring stations is not uniform across Vietnam. Indeed, stations with longer data series from the 1960s are typically more concentrated in the North, while many hydrometeorological monitoring stations in the South of Vietnam have only been operational since the late 1970s. Using data series of varying period lengths to calculate the average rainfall over an area may lead to errors in the results. Hence, studies assessing the characteristics and trends of rainfall and extreme rainfall in Vietnam should prioritize ensuring data uniformity across the data period.

The existing studies on precipitation extremes in Vietnam have largely centered on analyzing their trends. However, to the best knowledge of the author, no investigation has been conducted on the probability distribution of extreme rainfall values in Vietnam. According to the Generalized Extreme Value (GEV) theory (Beirlant et al., 2004), the maximum, minimum, or values that exceed a certain threshold in a selected time period of a data series will follow a theoretical distribution, allowing for the estimation of the probability of extreme events, as well as their return periods. Such information would prove invaluable in the planning of responses to extreme rainfall events across sectors such as transport, construction, agriculture, and health.

To address the gaps identified above, this study will analyze rainfall characteristics, trends and return periods of cerain rainfall extremes in Northern Vietnam - an area with a high number of monitoring stations that have comprehensive data covering the period 1961-2018. Section 2 provides a detailed description of the data and methodology, while Section 3 presents the results and discussion. Finally, the conclusion is presented in Section 4.

2. Data source, study area, and methodology

2.1. Data source and study area

This study utilized daily rainfall data (R) collected from the network of meteorological stations in Vietnam operated by the Vietnam Meteorological and Hydrological Administration (VNMHA). As one of the main objectives of this study was to investigate trends in rainfall extremes in the past, thus only stations with a long data record spanning from 1961 to 2018 were selected. To ensure data quality, we excluded any month with more than five days of missing data and any year with more than 30 days of missing data. Moreover, stations with more than 5 years of missing data within the 58-year period 1961-2018 were considered defective and were also excluded. Applying these filtering criteria, we identified a total of 37 meteorological stations mainly located in the Northern region of Vietnam (from Ha Tinh station [18.35°N,105.90°E] northward) that met our requirements, in addition to a few stations located in other parts of Vietnam.

The locations of the 37 selected meteorological stations are shown in Fig. 1, while detailed information on their names and locations can be found in Table 1. These stations are distributed across four climatic sub-regions of Vietnam, including 5 stations in the Northwest (N1), 10 stations in the Northeast (N2), 12 stations in the Northern Delta (N3), and 10 stations in the North Central region (N4). These four climatic sub-regions are among the seven identified in Vietnam based on the criteria proposed by Nguyen and Nguyen (2004).

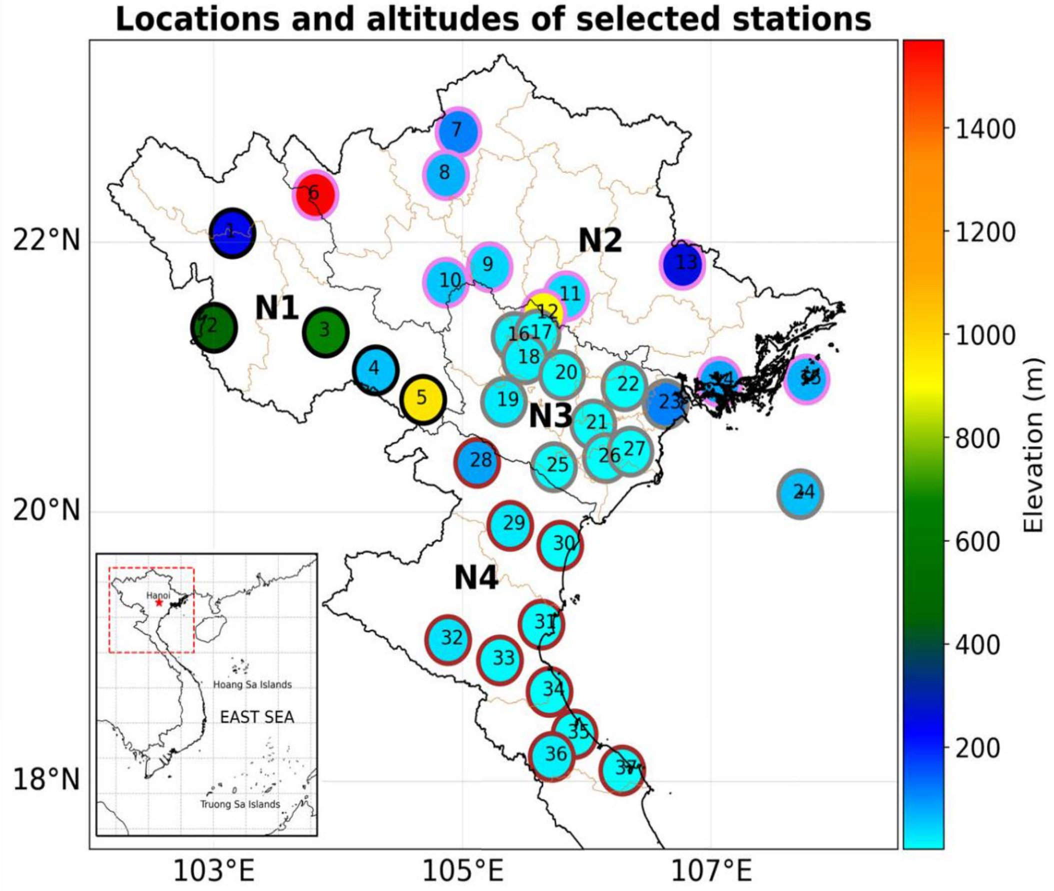

Figure 1. Locations and altitudes of 37 selected meteorological stations in Northern Vietnam. The circle symbols represent the location of each station, with the number corresponding to the ordinal number of the station in Table 1. The border color of each station indicates its climatic sub- region, including black for the Northwest region, purple for the Northeast region, gray for the North Delta region, and brown for the North Central region

2.2. Identification of rainy and dry seasons, and computation of extreme rainfall indices

At each station, several average rainfall characteristics for the study period are analyzed, including the total annual rainfall and the contribution of rainfall in both wet and dry seasons. To identify the climatological rainy season, monthly climatological rainfall series are first computed. The rainy season is then defined as the consecutive months of the year with a climatological monthly rainfall exceeding 100 mm, and a probability of occurrence greater than 50% for the same months during 1961-2018, where the rainfall value exceeds 100 mm. The remaining months of the year are considered as the dry season.

In addition to average rainfall characteristics, 9 extreme rainfall indices were selected to evaluate the variation and trend of extreme rainfall events in terms of both frequency and intensity. The list and definitions of these indices are provided in Table 2.

Table 1. Names and locations (longitude and latitude) of 37 selected meteorological stations in Northern Vietnam

No.	Station	Latitude (ºN)	Longitude (ºE)	No.	Station	Latitude (ºN)	Longitude (ºE)
Region N1				19	Hoa Binh	20.817	105.333
1	Lai Chau	22.067	103.150	20	Ha Noi	21.017	105.800
2	Dien Bien	21.367	103.000	21	Hung Yen	20.650	106.050
3	Son La	21.333	103.900	22	Hai Duong	20.933	106.300
4	Yen Chau	21.050	104.300	23	Phu Lien	20.800	106.633
5	Moc Chau	20.833	104.683	24	Bach Long Vi	20.133	107.717
Region N2				25	Nho Quan	20.333	105.733
6	Sa Pa	22.350	103.817	26	Nam Dinh	20.400	106.150
7	Ha Giang	22.817	104.967	27	Thai Binh	20.450	106.350
8	Bac Quang	22.500	104.867	Region N4			
9	Tuyen Quang	21.817	105.217	28	Hoi Xuan	20.367	105.117
10	Yen Bai	21.700	104.867	29	Bai Thuong	19.900	105.383
11	Thai Nguyen	21.600	105.833	30	Thanh Hoa	19.750	105.783
12	Tam Dao	21.467	105.650	31	Quynh Luu	19.167	105.633
13	Lang Son	21.833	106.767	32	Con Cuong	19.050	104.883
14	Bai Chay	20.967	107.067	33	Do Luong	18.900	105.300
15	Co To	20.983	107.767	34	Vinh	18.667	105.700
Region N3				35	Ha Tinh	18.350	105.900
16	Viet Tri	21.300	105.417	36	Huong Khe	18.183	105.717
17	Vinh Yen	21.317	105.600	37	Ky Anh	18.083	106.283
18	Son Tay	21.133	105.500				

Table 2. Rainfall indices used in the study. In addition to yearly values calculated for all indices, seasonal values for three indices (PRCPTOT, WDAY, and SDII) are also estimated separately for both the dry and wet seasons, and denoted as PRCP_DRY, WDAY_DRY, SDII_DRY, and PRCP_WET, WDAY_WET, and SDII_WET, respectively

Extreme Index	Definitions	Units
WDAY	Annual or seasonal count of wet days when precipitation is greater than or equal to 1 mm	days
PRCPTOT	Annual or seasonal total precipitation in wet days	mm
SDII	Simple precipitation intensity index, which is the average precipitation from wet days	mm/day
R16mm	Annual count of days when precipitation is greater than or equal to 16 mm. 16 mm/day is the threshold used by the VNMHA to classify a day as having moderate rainfall	days
R50mm	Annual count of days when precipitation is greater than or equal to 50 mm. 50 mm/day is the threshold used by the VNMHA to classify a day as having heavy rainfall	days
RX1day	Annual maximum 1-day precipitation	mm
RX5day	Annual maximum consecutive 5-day precipitation	mm
CDD	Annual maximum number of consecutive dry days where dry days are days with daily precipitation < 1 mm	days
CWD	Annual maximum number of consecutive wet days	days

2.3. Trend analysis method

The Sen's method, originally proposed by Sen (1968), is applied for trend analysis in this study. The statistical significance levels of the Sen's slope are determined using the nonparametric Mann-Kendall test (Kendall, 1975). One of the advantages of using the Sen's method over the linear trend is that it compares the relative values of the data series elements, thereby avoiding spurious trends that may arise from the presence of outliers. Moreover, the Mann-Kendall test is employed because it is not necessary to know the underlying distribution of the sample set. The significance level is set to 0.05 for all trend analyses conducted in this study.

2.4. Calculation of return values for selected extreme indices

The return value (RV) of an extreme event refers to the expected value of that event occuring again in a given period of time. To calculate RVs, it is necessary to know the distribution function form of the value series. In this study, we examine the distribution and RVs of RX1day and RX5day at the 37 selected stations, due to their block maximum characteristic, i.e. these two indices represent the maximum values within a given block of data, which are assumed to be independent and identically distributed. It should be noted that the remaining 7 extreme indices listed in Table 2 do not possess the block maximum characteristic. According to the extreme value theory (Beirlant et al., 2004), the distribution of the RX1day (or RX5day) series follows the generalized extreme value (GEV) distribution function, which is expressed as follows:

$$G(X) = exp\left[-\left\{1 + \xi(\frac{X-\mu}{\sigma})\right\}^{-1/\xi}\right] \quad (1)$$

The GEV distribution is characterized by there parameters: location (μ), scale (σ), and shape (ξ). The location parameter μ is the value around which the distribution is centered; the scale parameter σ controls the spread of the distribution; and the shape parameter ξ determines the tail behavior of the distribution. *G(X)* has a Gumbel distribution with ξ approaching 0, a Fréchet distribution with $\xi > 0$, and a Weibull distribution with $\xi < 0$. For the given RX1day or RX5day data series, a GEV fit is performed via the genextreme package in Python's Scipy library using Maximum Likelihood Estimation (MLE). This MLE process allows for the estimation of the three parameters μ, σ, and ξ that best fit the data series to the GEV distribution.

Based on the GEV distribution function, the return period T of an event in which RX1day (or RX5day) reaches a given value X_T is estimated, satisfying the following condition:

$$G(X_T) = 1 - 1/T \quad (2)$$

In Section 3.3, we compute the RX1day and RX5day values that occur only once every 5 years and 10 years between 1961-2018. We then investigate whether the frequency of occurrence of these values has increased or decreased in the last 30 years (1999-2018).

3. Results and discussion

3.1. General rainfall characteristics in Northern Vietnam

Figure 2 presents fundamental information on rainfall characteristics at 37 selected stations across four climatic sub-regions in Northern Vietnam. Annual total rainfall averages vary significantly, ranging from 1140 mm (Hoi Xuan station in N4) to 4758 mm (Bac Quang station in N2). The annual total rainfall averages for stations in the N1, N2, N3, and N4 regions are approximately 1600 mm, 2300 mm, 1650 mm, and 2000 mm, respectively. The N2 region exhibits the highest annual total rainfall average due to a considerable contribution from the Bac Quang rain center. Notably, Bac Quang station recorded the highest annual rainfall amount of 6466mm in 1971, while Quynh Luu station experienced a minimum of 651 mm in 1995. The onset and duration of the rainy season vary across climatic sub-regions (Fig. 2b). In the N1 region, the rainy season typically begins in April and ends in September. In the N2 region, the rainy season also begins in April but lasts until October, except for certain stations such as Sa Pa, which experience a rainy season from March to November, while Lang Son, Bai Chay, and Co To stations have a rainy season beginning in May. In both the N3 and N4 regions, the rainy season begins in May and ends in October, with a possible extension until November or December for stations located in the southern part of N4.

Based on the results of the above rainy season analysis, the contribution of rainy season precipitation to the annual total rainfall is calculated. Fig. 2c indicates that this contribution level varies across stations, ranging from 73% (Lang Son) to 92% (Sa Pa and Bac Quang). It is worth noting that stations with a higher contribution level often experience a longer rainy season than the average of 6-7 months. For instance, Sa Pa, Bac Quang, and Ky Anh stations have a rainy season lasting 9 months, 8 months, and 8 months, respectively, and all exhibit contribution levels of at least 88%. On the other hand, stations with the lowest contribution level, namely Lang Son (73%) and Bach Long Vi (76%), have a shorter rainy season that lasts only 5 months.

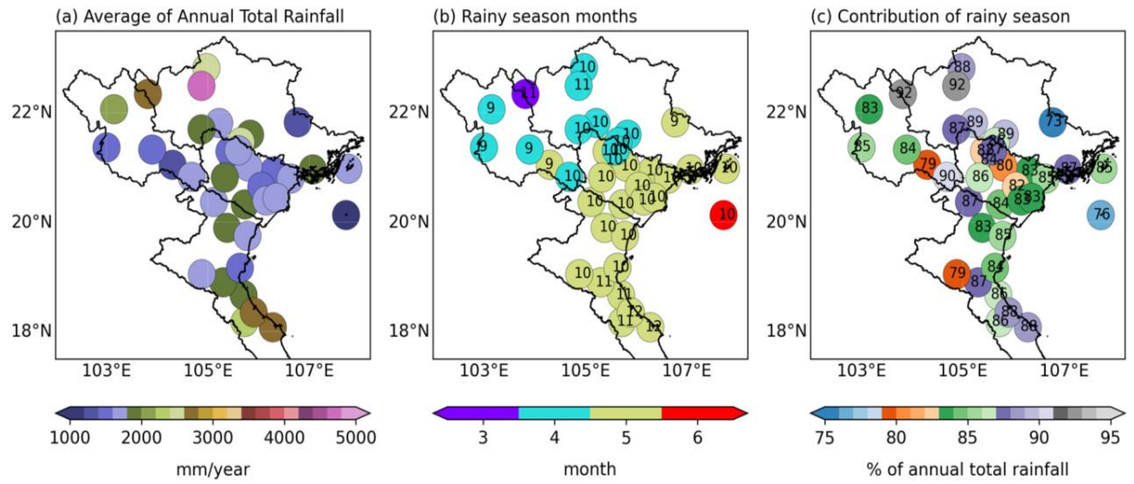

Figure 2. (a) Average annual total rainfall (mm/year) across 37 selected stations; (b) Onset and ending months of the rainy season, where the color denotes the month of the season's onset and the number in the circle represents the month of its end; and (c) Contribution of rainfall during the rainy season to the annual total rainfall expressed as a percentage (%)

Figure 3 displays the average annual total rainfall for each decade in the form of a box plot. Due to incomplete data availability, the values for the first and last decade are calculated using the average of 9 years only (1961-1969 and 2010-1018). It can be seen that the third quantile threshold value (75th percentile) of rainfall over all periods is generally below 2000 mm/year. From the decade 1970-1979 to the decade 2000-2009, the median, lower and upper quartile values exhibit a decreasing trend. However, in the last decade (2010-2018), there appears to be a marked increase, both in the median value and the lower and upper quartiles. This suggests that the long-term trend of rainfall over the region may be reversing. Further exploration of these trends are conducted in the subsequent sub-section.

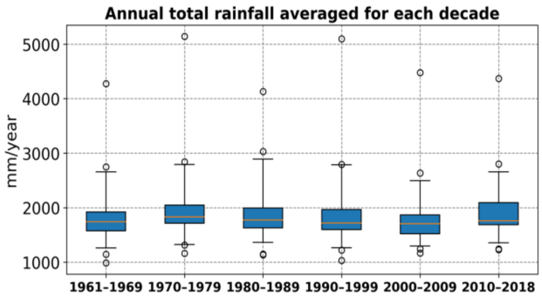

Figure 3. Box plot showing the distribution of average annual rainfall for each decade across 37 stations. The box represents the central 50% of the data, with the median value indicated by the orange line. The lines extending from the box capture the 10^{th}-90^{th} percentile ranges of the data, while the wiskers denote values below 5^{th} percentile or above 95^{th} percentile. Unit in mm/year

3.2. Past trends of rainfall extremes

Figure 4 illustrates the trends of PRCPTOT at the selected stations in Northern Vietnam. It can be seen that the annual PRCPTOT values at most stations have decreased over time, with only a few stations showing an increasing trend, including four stations in N1, three stations in N2, one station in N3, and four stations in N4. It is worth noting that the overall increase and decrease in rainfall across the stations are mostly not statistically significant. Only Thai Nguyen station has a significant decrease of -3%/decade, and Bach Long Vi station has a significant increase of 5.2%/decade.

The trend in the PRCPTOT of the rainy season (PRCP_WET) is consistent with the trend observed in annual PRCPTOT, given the significant contribution of rainy season rainfall to the annual rainfall. Meanwhile, the PRCPTOT of the dry season (PRCP_DRY) experiences an increasing trend at most stations in N1, N2 and N4, with only Do Luong station showing a statistically significant increase of 7.1%/decade. In the North Delta (N3) region, most stations still exhibit a decreasing trend in PRCP_DRY, although none of these trends are statistically significant.

The trends in the number of wet days per year and per season are depicted in Fig. 5. Most stations across all four regions experience a decreasing trend in annual WDAY. Notably, N2 has five stations and N3 has two stations showing statistically significant decreasing trends. The station with the largest decrease (-3.5 days/decade) in WDAY is Ha Giang. Although a few stations in Northern Vietnam experience a slight increase in WDAY, the changes are not statistically significant. In both the rainy and dry seasons, WDAY also tends to decrease across most stations. The increase in PRCP_DRY (Fig. 4c) and the decrease in WDAY_DRY (Fig. 5c) suggest that the SDII rainfall intensity index is likely to increase in the dry season for most stations, as confirmed in Fig. 6c.

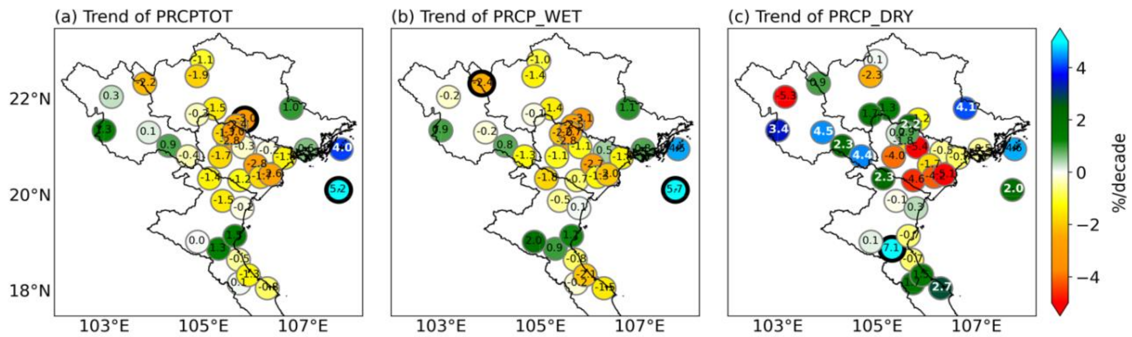

Figure 4. Trends in (a) annual PRCPTOT, (b) PRCP_WET, and (c) PRCP_DRY. Stations with a statistical significant trend at the 0.05 level are circled in black, while stations that do not reach the significance level are circled in gray

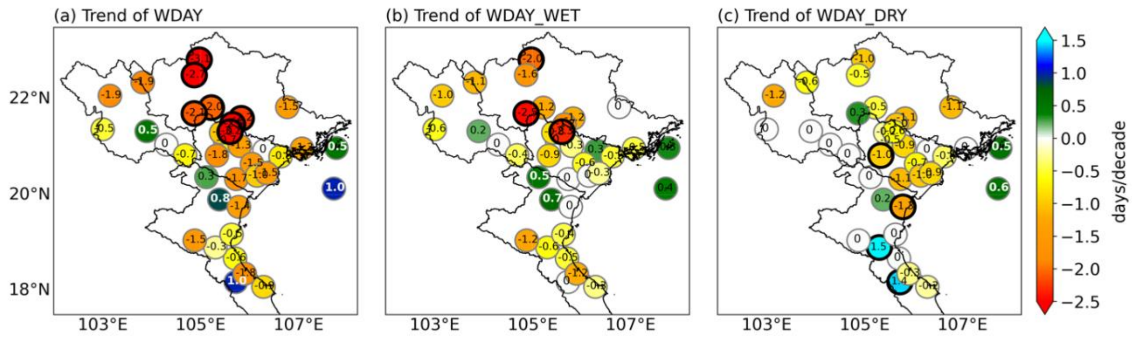

Figure 5. As in Fig. 4 but for WDAY

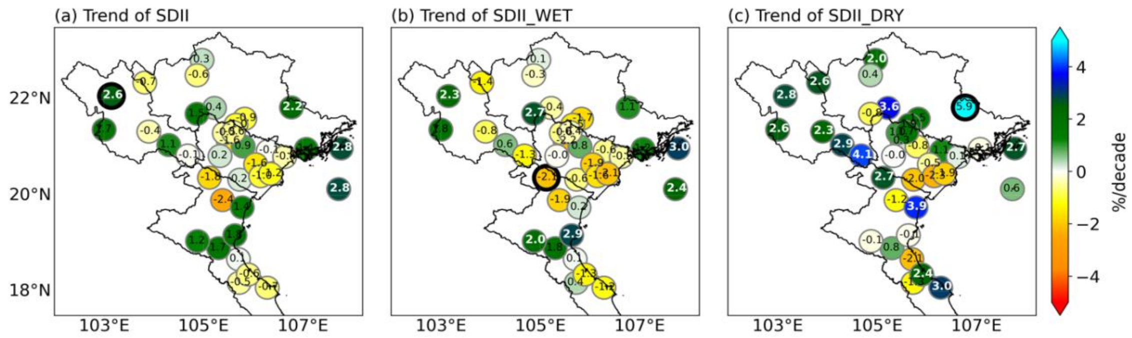

Figure 6. As in Fig. 4, but for SDII

Figure 7 illustrates the trend of the SDII rainfall intensity index. In contrast to the trends of PRCPTOT and WDAY, the number of stations where SDII tends to increase is greater than the number of stations where it tends to decrease, particularly in the dry season. This is because WDAY tends to decrease while PRCPTOT does not decrease proportionally, resulting in an increase in rainfall intensity. For both the annual and rainy season SDII values, the increase or decrease in SDII is not statistically significant at most stations, except for Lai Chau station in N1 with an annual SDII increase of 2.6%/decade, and Hoi Xuan station in N4 with a decrease of -2.1%/decade. During the dry season, SDII tends to increase at most stations in N1, N2, and N4, with Lang Son station (5.9%/decade) and Thai Nguyen station (6%/decade) showing statistically significant increasing trends. In N3, many stations show a tendency for SDII_DRY to decrease, which can be attributed to a large decrease in PRCP_DRY despite the decrease in WDAY_DRY. For instance, Ha Noi station and Thai Binh station experience a large decrease of -5.4% and -5.1% per decade, respectively, in PRCP_DRY (Fig. 4).

RX1day exhibits a tendency to increase at most stations in N4 (except for Hoi Xuan station), and at 2 out of 5 stations in N1, and 7 out of 10 stations in N2. However, these increases are not statistically signficant. In contrast, most stations in N3 show a decreasing trend in RX1day, which is also observed in RX5day. When combined with the SDII results, it suggests that the magnitude and intensity of rainfall have decreased over the North Delta region during 1961-2018. However, extreme rainfall has exihibited an increasing trend in certain places such as North Central, the island stations, and certain elevated stations like Lang Son and Lai Chau.

The trend of moderate rainy days per year is inconspicuous across most stations (Fig. 8a). Many stations do not show any trend. Only a few stations exhibit a trend: Co To station in N2 (1.15 days/decade), Bac Quang in N2 (-2 days/decade), Tam Dao in N3 (-1.15 days/decade) and Vinh Yen in N3 (-1.43 days/decade). In general, the number of stations with a decreasing trend in moderate rainy days is slightly higher than that of stations with an increasing trend.

Meanwhile, most stations in Northern Vietnam exhibit no trend or a very slight increase or decrease in the number of heavy rainy days per year. Only Thai Binh station and Bach Long Vi station in N3 have a decreasing (-0.51 days/decade) and increasing (0.41 days/decade) trend, respectively, which are statistically significant.

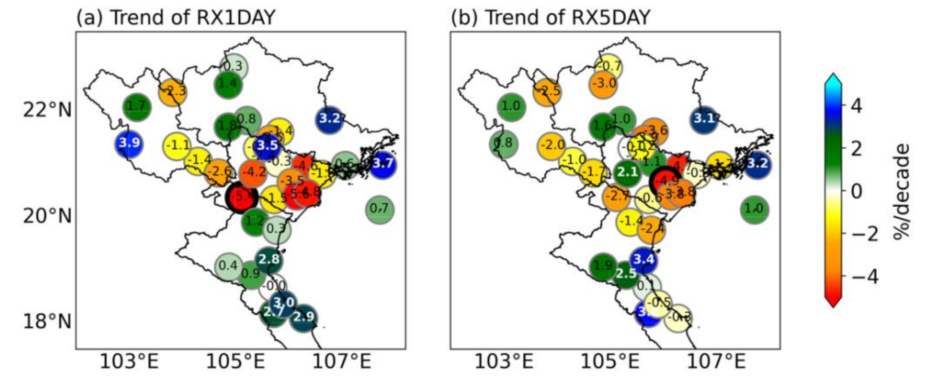

Figure 7. Trends of (a) RX1day and (b) RX5day in the period 1961-2018

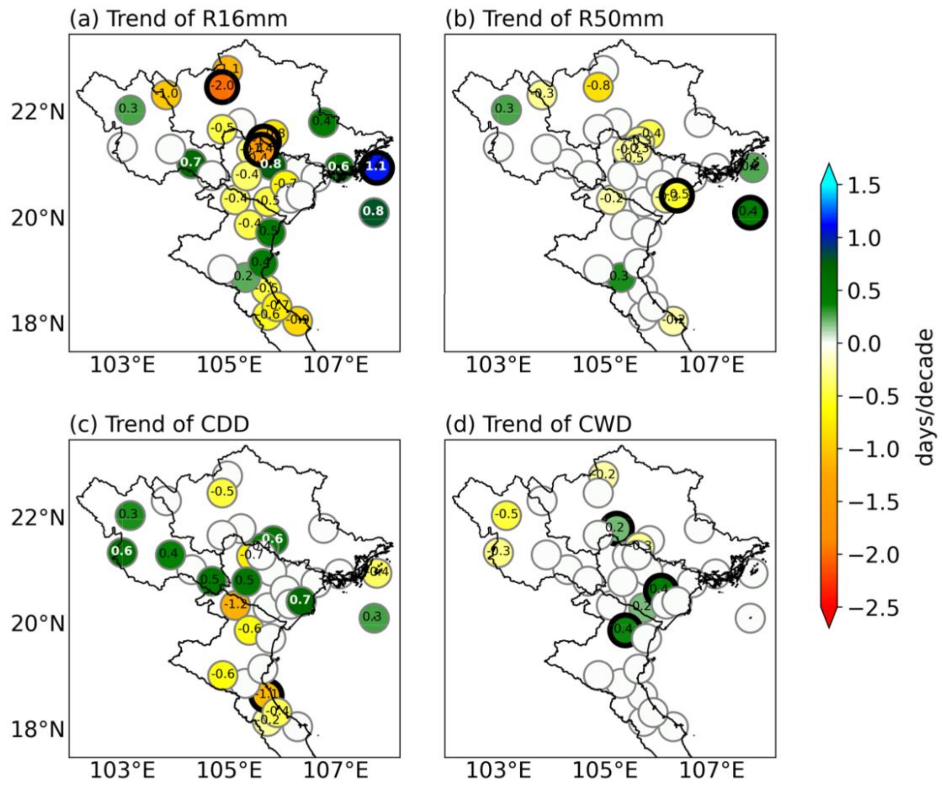

Figure 8. Trends of (a) R16mm, (b) R50mm, (c) CDD, and (d) CWD across stations for the period 1961-2018. Stations with a statistical significant trend at the 0.05 level are circled in black

For the period 1961-2018, most stations also demonstrate no trend for CDD and CWD. The CDD exhibits a slight increase at some stations in N1 and N3, suggesting that the number of consecutive dray days resulting in possible arid conditions has slightly increased in these areas over the past decades. CDD shows a slight decrease at some stations in N4, with only Vinh station experiencing a statistically significant decrease, reaching -1.11 days/decade. Regarding CWD, only 8 out of 37 stations across the region have a non-zero CWD trend. There are only 3 stations with a statiscally significant increase in CWD, including: Tuyen Quang (0.21 days/decade), Hung Yen (0.4 days/decade) and Bai Thuong (0.36 days/decade).

Figure 9 provides a summary of the trend of the studied indices across stations in Northern Vietnam in the form of box plots. At most stations, we observe a decreasing trend in PRCPOT and PRCP_WET, along with an increasing trend in PRCP_DRY. Furthermore, there has been a declining trend in annual and seasonal (rainy season and dry season) wet days at most stations. Conversely, annual and seasonal SDII have increased at most stations, primarily due to a decrease in the number of wet days and resulting in an increase in rainfall intensity. This trend is particularly pronounced during the dry season, which can be attributed to the fact that most stations in the region have experienced an increase in PRCP_DRY. For RX1day, RX5day, R16mm, and R50mm, the number of stations showing a decreasing trend is greater than those showing an increasing trend. Finally, most stations in Northern Vietnam exhibit no trend for CDD and CWD.

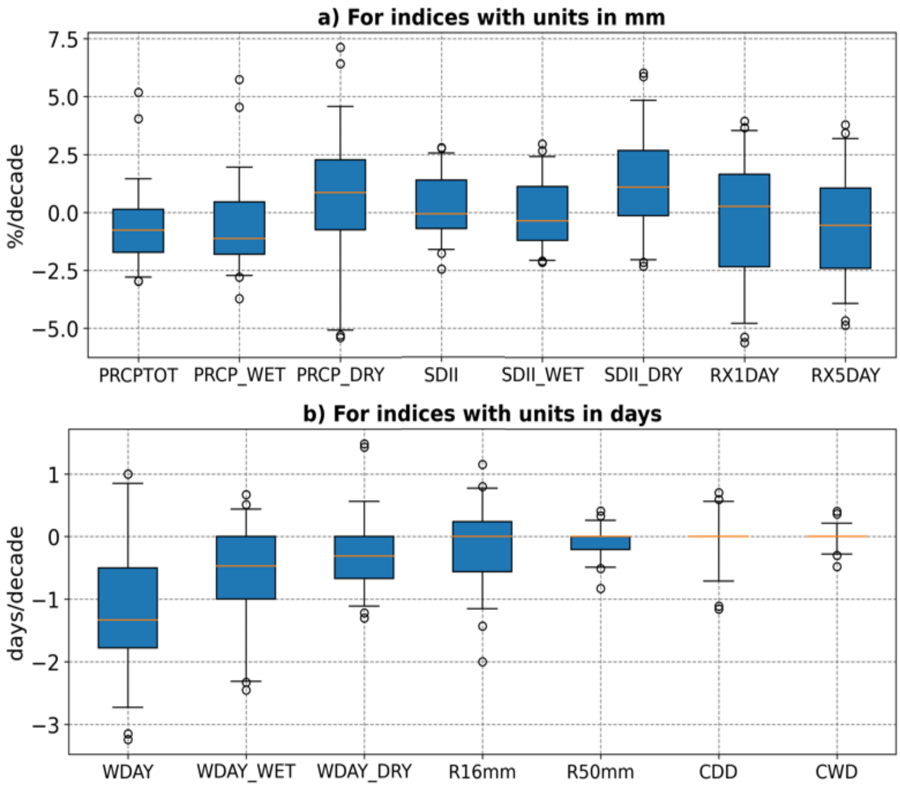

Figure 9. Box plot showing the distribution of the extreme rainfall indices across 37 stations in the period 1961-2018. The box represents the central 50% of the data, with the median value indicated by the orange line. The lines extending from the box capture the 10^{th}-90^{th} percentile ranges of the data, while the wiskers denote values below 5^{th} percentile or above 95^{th} percentile

3.3. Return values of extreme rainfall

Across the four climatic sub-regions, both RX1day and RX5day conform to GEV distributions with a Weibull form due to $\xi<0$ (Fig. 10). The RX1day values in the regions from N1 to N3 are concentrated around 80-120 mm/day, with relatively higher values observed in N2 compared to N1 and N3. Meanwhile, the N4 region typically experiences larger RX1day values, centered around 100-200 mm/day.

Regarding RX5day, Fig. 10 shows that its distribution shifts to the right, i.e. towards higher values, as one moves from N1 to N3, and then to N2 and N4. Specifically, RX5day values are concentrated around 100-220 mm in N1, 120-250 mm in N3, 120-320 mm in N2, and 180-420 mm in the N4 region.

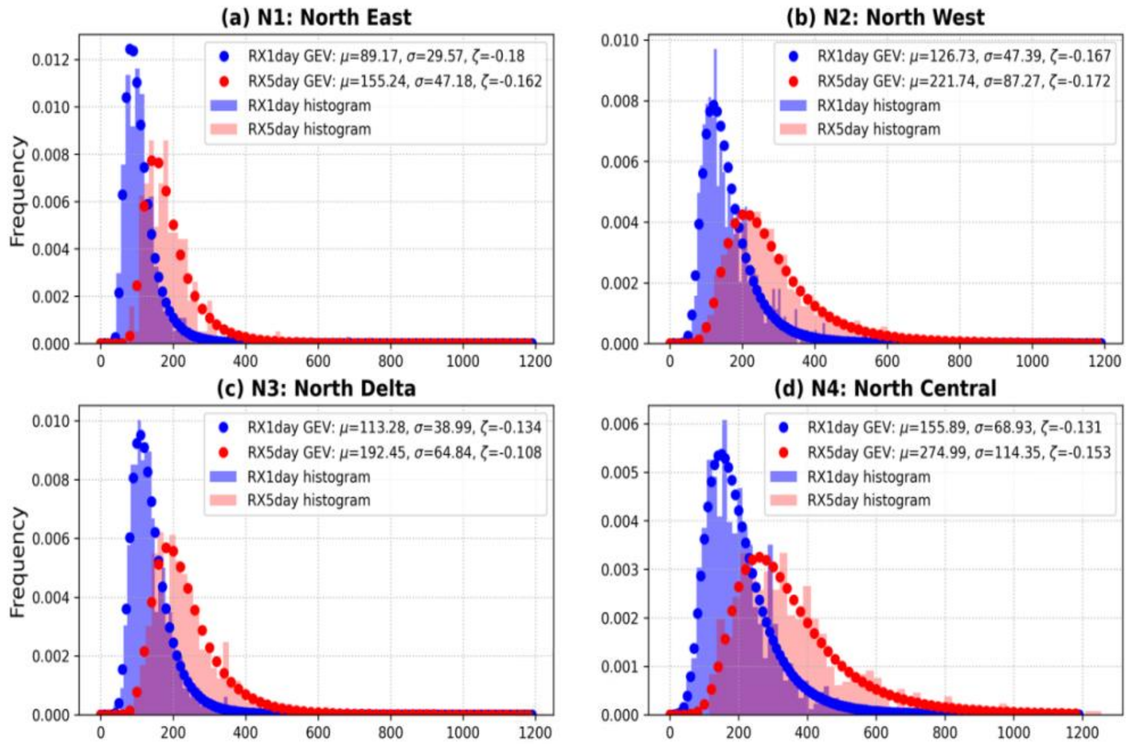

Figure 10. Histogram and best fit GEV distribution (dots) of RX1day (blue) and RX5day (red) for 4 sub-climatic regions (N1-N4). The location parameter (μ), scale parameter (σ), and shape parameter (ξ) of the GEV distribution are shown. The horizontal axis represents rainfall values in mm

Figure 11 presents the RVs of RX1day and RX5day over 5-year (RV5) and 10-year (RV10) return periods for the study period 1961-2018. It is evident from the figure that the N4 region is more susceptible to extreme rainfall events. The highest RV5 of RX1day in Northern Vietnam is found at Ha Tinh station, reaching 361 mm. Meanwhile, for a 10-year return period, the maximum RV10 is found at Ky Anh station, reaching 437 mm. The largest RX1day observed during the period 1961-2018 was 788 mm, recorded at Do Luong station on September 27, 1978, surpassing the RV10s across the entire Northern region.

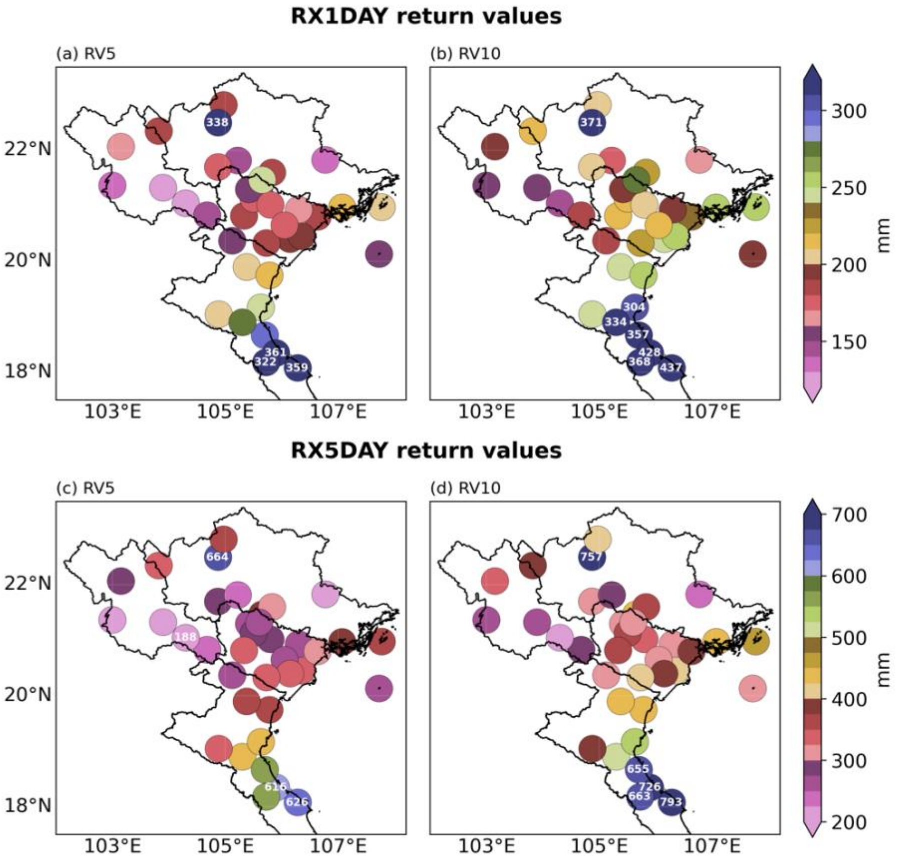

Figure 11. 5-year (left) and 10-year (right) return values of RX1day (upper) and RX5day (lower) for 37 selected stations, based on the GEV distribution. For clarity and ease of discussion, return values are displayed at each station location as a written number, but only if they exceed 300 mm 300 mm (600 mm) or fall below 100 mm (200 mm) for RX1day (RX5day)

Regarding RX5day, the largest RV5 if found at Bac Quang station, reaching 664 mm. The largest RV10 is 793 mm, found at Ky Anh station. The maximum value of RX5day observed in the period 1961-2018 was 1254 mm at Ky Anh, which occurred from October 16 to October 20, 1993, also far exceeding the RV10s throughout the North. The RV5s and RV10s for RX1day (RX5day) are commonly less than 200 mm (400 mm) and 260 mm (500 mm), respectively, over the N1-3 regions, with the exception of the Bac Quang rain center.

Figure 12 illustrates the normalized frequency of occurrence (OFreq) of the RV5 and RV10 events during the last 30 years (1989-2018), compared to the period from 1961 to 2018. OFreq values greater than 1 (less than 1) suggest a shorter (longer) return period for the coresponding RV, indicating an increase (decrease) in the frequency extreme rainfall events in recent decades. The results indicate significant variability in OFreq values across the stations in the domain. Generally, the number of stations with OFreq less than 1 exceeds those with OFreq greater than 1. Out of the 37 stations, only 1 station (Lai Chau) and 3 other stations (Co To, Tuyen Quang, and Phu Lien) exhibit OFreq greater than 1 for all the four cases and at least three cases considered in Fig. 12, respectively. Meanwhile, the station numbers with OFreq less than 1 are 5 and 8, respectively. This suggests that in Northern Vietnam, the frequency of extreme rainfall events exceeding the RV5 and RV10 thresholds of 1961-2018 has decreased in recent decades at many stations.

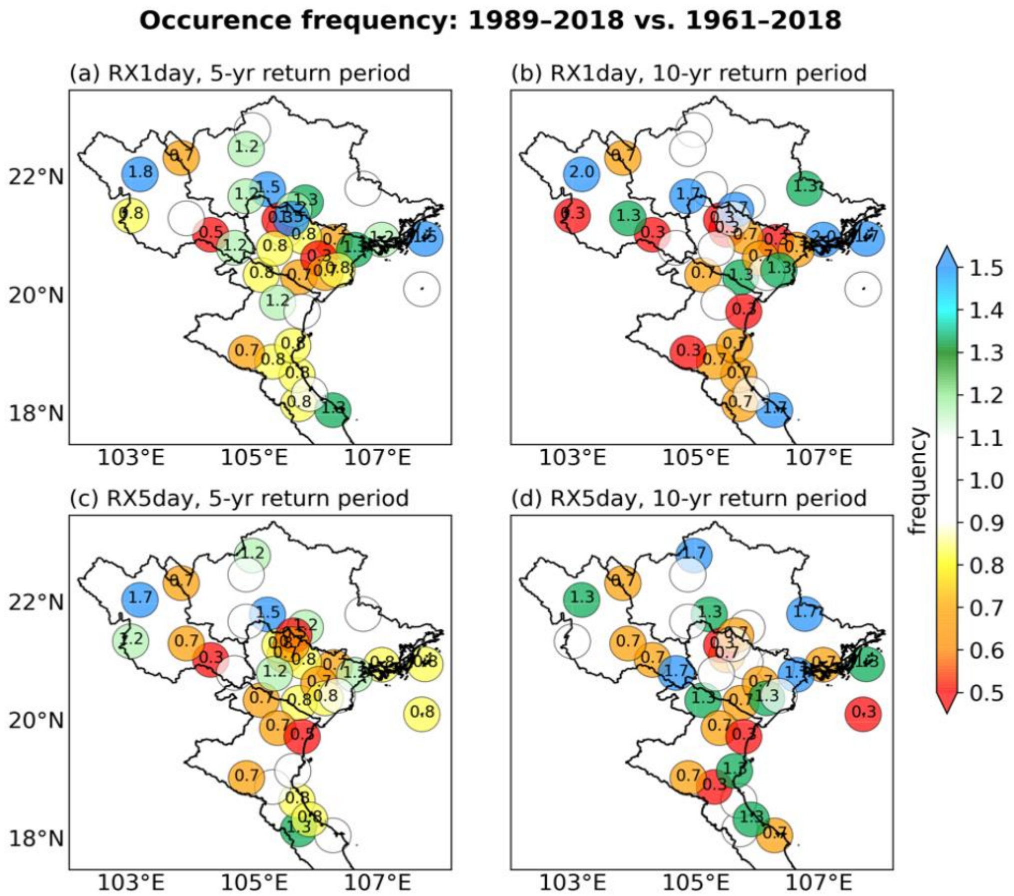

Figure 12. Normalized frequency of occurrence (Ofreq) of RX1day (upper) and RX5day (lower) values with 5-year (left) and 10-year (right) return periods during the recent 30 years (1989-2018 compared to the entire period 1961-2018. Ofreq values greater than 1 indicate an increase in the frequency of extreme events, while values less than 1 indicate a decrease

3.4. Discussions

In this study, for the first time, detailed information on the rainy season months is calculated and presented for each station with updated monitoring data sources (Fig. 2b). The late ending of the rainy season in N4 compared to other regions is attributed to the winter monsoon that brings moisture from the sea and interacts with the topography in this area (Ngo-Duc et al., 2013; Nguyen-Le et al., 2015).

It is worth noting that some previous studies have reported a decreasing trend in rainfall in Northern Vietnam (e.g. MONRE 2009; MONRE 2012; Ngo-Duc and Phan-Van 2012; Endo 2009). The present study also confirms that this trend continues to prevail at stations in the region, albeit with a less significant decrease. This difference may be due to the fact that the rainfall datasets used in previous studies were generally collected prior to 2010, whereas the average rainfall has increased considerably in the last decade in comparison to previous ones (as shown in Fig. 3), thereby offsetting the decreasing trend.

According to MONRE (2016), six out of the 37 selected stations underwent a change in location during the study period (Table 3). Relocating a station could alter the rainfall pattern and distribution of the station, which implies that we need to be cautious and may need to perform more detailed analysis in the future for these stations.

Table 3. List of stations in Northern Vietnam that experienced changes in their locations during the study period, along with the corresponding year of change (source: MONRE 2016)

Stations	Year of location change
Sa Pa	1979
Viet Tri	1965, 1973, 1992, 2001, 2003
Bai Chay	1974, 2003
Hung Yen	1962, 2013
Thanh Hoa	1993
Vinh	1956, 1959, 1970, 1974, 1981

The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2021) demonstrated that a 10-year RV of heavy rainfall over land in the pre-industrial period 1850-1900 would occur on average 1.5 times, 1.7 times, and 2.7 times in 10 years at the 1.5°C, 2°C, and 4°C Global Warming Levels (GWL), respectively. This indicates that the OFreq of extreme rainfall events is projected to increase with global warming. However, the present study does not show any systematic increase in the frequency of extreme rainfall events in Northern Vietnam. Instead, a decreasing trend prevails in most stations. It should also be noted that the limited numbers of data inputs (58 values representing 58 years) can affect the accuracy of the best fit GEV distribution, hence affecting the RVs and frequency calculation of extreme event at a station.

The RVs depicted in Fig. 12 have considerable practical implications. These values can serve as a reference to inform policy-making and practical applications, such as designing traffic works, drainage systems, irrigation, and dike construction in Northern Vietnam.

4. Conclusions

In conclusion, this study provides valuable insights into the characteristics and changing patterns of extreme rainfall in Northern Vietnam over the past several decades. The results indicate that there is significant variability in annual rainfall averages across stations, with rainy season precipitation contributing considerably to the total annual rainfall. Most stations show a decreasing trend in annual total rainfall in wet days and the number of wet days, while rainfall intensity has increased in most stations, particularly during the dry season. The number of stations displaying a decreasing trend in the annual maximum 1-day precipitation, consecutive 5-day precipitation, and the number of moderate and heavy rainfall days is higher than those showing an increasing trend. Furthermore, the frequency of extreme rainfall events exceeding the 5-year and 10-year return values of 1961-2018 has decreased in recent decades at many stations.

In light of the context of global warming, this study suggests that extreme rainfall events in Northern Vietnam may become more intense and less frequent. Moreover, this study highlights the need for stakeholders and policy makers to incorporate changing patterns of extreme rainfall into their adaptation plans for the region. The spatial variability of the results further underscores the importance of considering station-specific characteristics when developing these plans.

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