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Extreme Precipitation Strongly Impacts the Interaction of Skewness and Kurtosis of Annual Precipitation Distribution on the Qinghai–Tibetan Plateau

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Abstract: Characterizing extreme precipitation precisely is crucial for predicting vegetation response to drought or storms. However, current precipitation generators in vegetation models do not simulate the occurrence and amount of extreme precipitation well. This study examined the effects of extreme precipitation on the skewness, kurtosis, and skewness–kurtosis interaction of annual precipitation distribution. The examination was based on theoretical calculations and monitoring data from 78 meteorological stations on the Qinghai–Tibetan Plateau (QTP). The results showed that extreme precipitation generally increased the skewness and kurtosis of annual precipitation distribution. A higher mean annual precipitation amplified the effects of precipitation extremes on promoting skewness and kurtosis in normal distribution scenarios. In contrast, these effects tended to be saturated for scenarios of higher mean annual precipitation in probability-based distributions. A reduction of dry days in a year markedly intensified the interaction of the skewness and the kurtosis, while the skewness–kurtosis interaction weakened with decreased maximum daily precipitation in a year. Moreover, the effect of extreme precipitation on the skewness–kurtosis interaction was stronger in arid or low-altitude areas. This study illustrates the fact that considering the skewness and kurtosis of annual precipitation distributions will be very helpful for simulating extreme precipitation on the QTP in the future. This will allow us to better understand the impact of climate change on alpine plants.

Keywords: alpine ecosystems; maximum daily precipitation; dry days; linear regression; altitude; climatic zones

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1. Introduction

Global climate change is greatly altering the intensity and frequency of climate extremes [1]. Historical records and climate models indicate that the magnitude and frequency of precipitation extremes are increasing at global, regional, and local scales [2–4]. Increasing maximum daily precipitation and continuous drought are major aspects of precipitation extremes [5–7]. The complexity and interactions of precipitation extremes make potential changes in precipitation distribution difficult to predict [8]. Global warming is increasing the difficulties associated with quantifying the risk of precipitation extremes [9]. Although climate models predict average precipitation conditions well, they often display bad performance when capturing the characteristics of precipitation extremes. Precipitation extremes, rather than means, determine the structure and functioning of ecosystems [10,11]. Moreover, failures in simulations of precipitation extremes will dramatically increase the uncertainties in predictions of vegetation dynamics from vegetation models [12].

Quantitative analysis of spatiotemporal changes in climate extremes is based on data recorded since 1950. The related research is rather uneven due to differences in the number and quality of these data in various regions of the world [13]. Evaluating the impacts of climate extremes is of great importance in regions lacking long-term recorded data, particularly developing countries with vulnerable ecosystems. This requires relatively reliable simulation of climate extremes. Linking climate extremes with statistical distributions may pave a road to the generation of reasonable climate data. Most studies to date have focused on the statistical properties of precipitation distributions or spatiotemporal patterns of precipitation extremes [14–16]. However, the relationship between precipitation extremes and the statistical properties of precipitation distributions, especially high-order moments like skewness and kurtosis, has been largely ignored. This knowledge gap hinders the accurate prediction of precipitation extremes. This further leads to overestimation or underestimation of the impacts of precipitation extremes on ecosystem dynamics. Even though precipitation extremes are assumed to relate closely to the skewness and kurtosis of precipitation distributions, the quantitative relationship should be clearly clarified. Ongoing attention has been paid to the roles of skewness and kurtosis in climate change, in addition to the roles of means and variability [5]. The skewness and kurtosis of precipitation distributions closely relate not only to the average conditions of precipitation, but also to precipitation extremes. The skewness and kurtosis may be more sensitive to the distribution of precipitation extremes than the mean. Using recorded weather data makes it difficult to disentangle the responses of various statistical properties to precipitation extremes. Statistical models provide a sound way to control target variables. In addition, simulations of long-term precipitation data based on mean values and standard deviations may underestimate precipitation extremes. Skewness and kurtosis can confirm the reasonability of predicted precipitation extremes. That is, skewness and kurtosis can be deemed sensitive probes for examining the magnitude and frequency of precipitation extremes. In addition, various types of precipitation extremes impact the statistical properties of precipitation distributions differently. The relationship between both may vary with environmental conditions and between ecosystem types.

To fill the above-mentioned knowledge gap, this study examined the effects of two indices of precipitation extremes, namely maximum daily precipitation and the number of dry days in a year, on the skewness and kurtosis of annual precipitation distribution on the Qinghai–Tibetan Plateau (QTP). Recent studies have shown that the climate of the QTP is becoming wetter, and precipitation extremes present a long-term increasing trend [17–20]. Historical precipitation data from 78 meteorological stations on the QTP were used to address the following questions: (1) What is the relationship between the skewness and kurtosis of the annual precipitation distribution? (2) How do precipitation extremes impact skewness and kurtosis along the gradient of mean annual precipitation? (3) Are there differences in the effects of precipitation extremes on skewness–kurtosis interactions among various altitudes and climate zones?

2. Materials and Methods

Qinghai–Tibetan Plateau (QTP) ecosystems are characterized by high climatic sensitivity and are very vulnerable to climate extremes. Studying the statistical features of climate data is of great importance to assessment of the ecological impacts of climate extremes on the QTP. The skewness and kurtosis of annual precipitation were calculated based on precipitation data from 78 meteorological stations on the QTP (Figure 1). These stations cover the major areas of the QTP, with altitudes from 1814 to 4900 m. The time period of these data ranged from 1960 to 2015. Years with more than 5% missing data were not included in the calculations.

2.1. The Relationship between Skewness and Kurtosis

I first examined the relationship between the skewness and kurtosis of annual precipitation to understand the precipitation distributional characteristics across the QTP (Figure 2). The skewness and kurtosis may vary with environmental conditions. Environmental conditions are mirrored by altitudinal differences. A threshold of 3500 m was used to differentiate high altitudes and low altitudes. High altitudes (>3500 m) and low altitudes (<3500 m) are characterized by different sensitivities to the intra-annual variability of daily precipitation on the QTP [21]. The intra-annual variability of daily precipitation greatly impacts the magnitude and frequency of precipitation extremes.

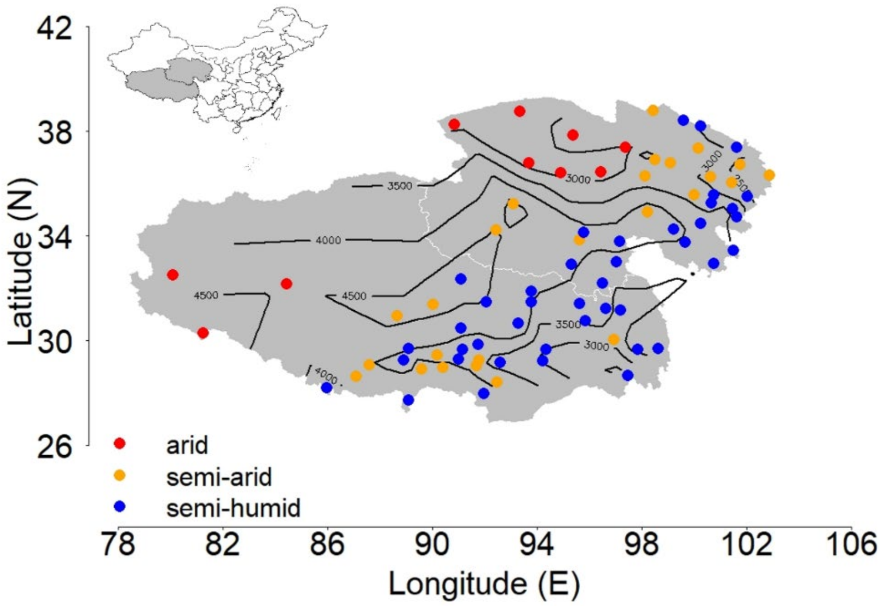

Figure 1. The locations of 78 meteorological stations on the QTP. Altitudes (contours) and precipitation zoning (circles) are given for these stations.

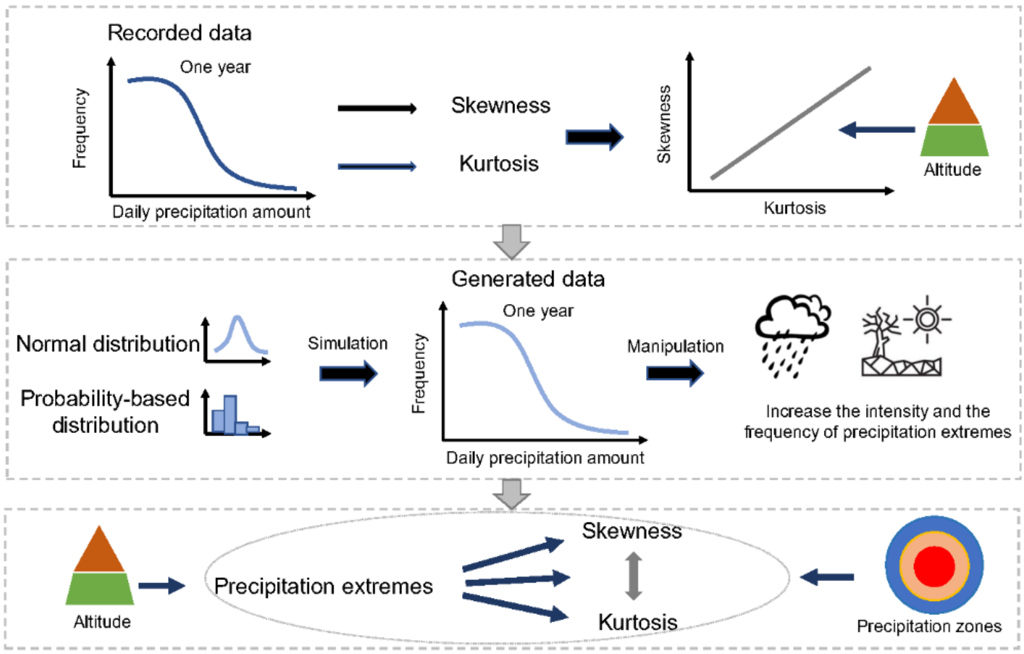

Figure 2. The conceptual graph of this study. First, the relationships between the skewness and kurtosis of the annual precipitation distributions were analyzed based on recorded weather data (upper grey dotted box). Second, statistical models were used to simulate the effects of precipitation extremes on the skewness and kurtosis (middle grey dotted box). Third, environmental conditions were considered in terms of the response of skewness–kurtosis interactions to precipitation extremes (lower grey dotted box).

2.2. Effects of Precipitation Extremes on Skewness and Kurtosis

To explore the effects of precipitation extremes on the skewness and kurtosis of annual precipitation, theoretical calculations were required. I therefore examined various scenarios along a gradient of mean annual precipitation (MAP) from 100 mm to 800 mm with an interval of 100 mm, based on the recorded precipitation data. Precipitation extremes were considered using two indices: annual maximum daily precipitation and the number of dry days (no precipitation) in a year. Annual precipitation was simulated in two ways using theoretical calculations: normal distribution and probability-based distribution. Both distribution types were used to generate time-series annual precipitation data. I then set rules to manipulate the generated precipitation data. This manipulation increased the intensity and the frequency of precipitation extremes.

In the normal distribution, the skewness and kurtosis were 0 and 3, respectively. A skewness of more than 0 is called right-skewed and one of less than 0 is called left-skewed. A kurtosis of more than 3 corresponds to a steep slope and one of less than 3 corresponds to a gentle slope. The parameters of the normal distribution included the average value and standard deviation of daily precipitation in a year. Higher annual precipitation usually leads to greater intra-annual variability of daily precipitation on the QTP [21]. That is, the standard deviation of daily precipitation increases with MAP (see Figure A1). In addition, the number of rainy days also increases with increasing MAP (see Figure A2). For each MAP, I randomly set 5000 repetitions of time-series data of annual precipitation. To evaluate the effects of precipitation extremes on the skewness and kurtosis of annual precipitation, I manipulated the annual maximum daily precipitation and the number of dry days simultaneously for each repetition. Specifically, ten maximum precipitation days were summed up to obtain the annual maximum daily precipitation (Equation (1)), and a value of zero was assigned to the other nine maximum precipitation days (Equation (2)).

$$Annualmaxprec^{1}_{after} = \sum_{n=1}^{10} Annualmaxprec^{n}_{before} \tag{1}$$

$$Annualmaxprec^{m}_{before} = 0 \tag{2}$$

where $Annualmaxprec^{1}_{after}$ denotes the daily maximum precipitation in a year after manipulation; $Annualmaxprec^{n}_{before}$ denotes the nth daily maximum precipitation in a year before manipulation. The range of m is from 2 to 10.

In the probability-based distribution, I classified the 78 meteorological stations based on the MAP gradient. For each MAP scenario from the gradient, I calculated the occurrence probability of daily precipitation at specific amounts, including less than 1 mm, 1 to 5 mm, 5 to 10 mm, 10 to 50 mm, and more than 50 mm. Similarly, I randomly set 5000 repetitions of the time-series data of annual precipitation for each MAP scenario based on the calculations. In this instance, three maximum precipitation days were summed up to obtain the annual maximum daily precipitation, and a value of zero was assigned to the other two maximum precipitation days, since the daily maximum precipitation in a year in the probability-based distribution was far higher than that in the normal distribution.

2.3. The Response of Skewness–Kurtosis Interactions to Precipitation Extremes

Precipitation extremes can also affect the relationship between the skewness and kurtosis of annual precipitation. Analyses were therefore performed for various altitudes and precipitation zones. Various precipitation zones shape different ecosystem types. These ecosystem types may modulate the impacts of precipitation extremes on the relationship between skewness and kurtosis. The meteorological stations were classified into different precipitation zones based on their MAPs [19]. The purpose of performing this analysis was to reasonably predict precipitation extremes for different environmental conditions and ecosystem types. All statistical analyses were performed using the linear regression model. The changing trend of the dependent variable was mirrored by the *slope* parameter of the model. The significance of the trend was mirrored by the *p*-value parameter of the model.

3. Results

3.1. The Relationship between Skewness and Kurtosis of Annual Precipitation

The skewness of the annual precipitation distribution was more than 0 for all the years and all the meteorological stations. Moreover, the kurtosis was more than 3 for all the analyzed data. The kurtosis of annual precipitation distribution was positively related to the skewness (Figure 3). The kurtosis values of meteorological stations at high altitudes tended to have a stronger effect on the skewness than those at low ones.

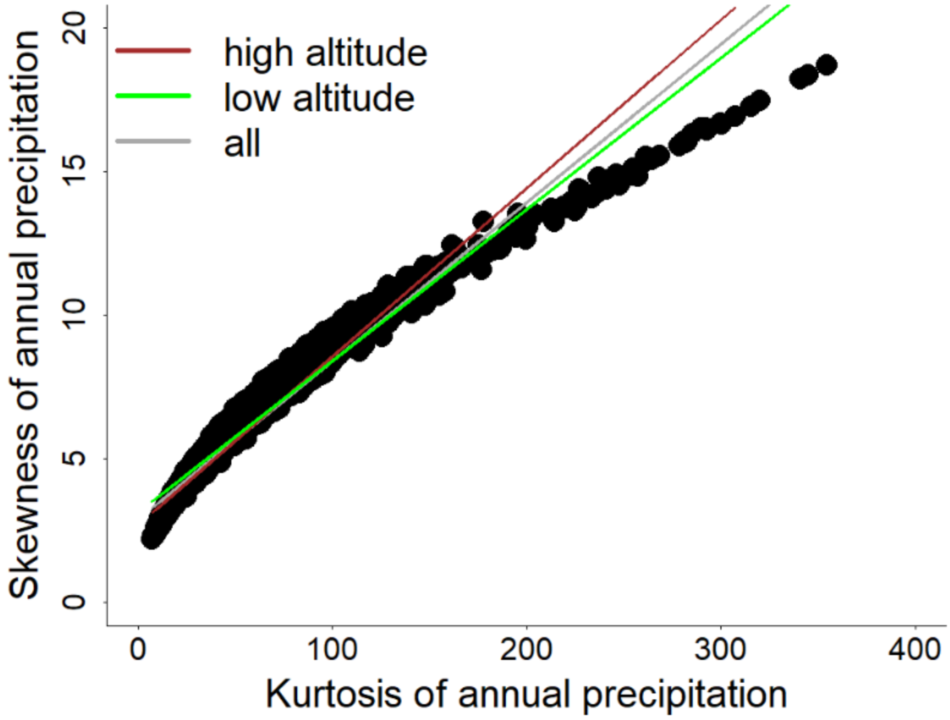

Figure 3. The relationship between the skewness and kurtosis of annual precipitation distributions based on recorded data from 78 meteorological stations on the QTP from 1960 to 2015. All three lines indicate results of linear regression. Different colors correspond to high-altitude stations (brown), all stations (grey), and low-altitude stations (green), respectively.

3.2. Effects of Precipitation Extremes on Skewness and Kurtosis of Annual Precipitation

Increases of annual maximum daily precipitation and the number of dry days generally increased the skewness and kurtosis of annual precipitation regardless of mean annual precipitation (MAP) or distribution type (Figure 4). In the normal distribution scenarios (Figure 4a,b), a higher MAP amplified the effects of precipitation extremes on the skewness and kurtosis of annual precipitation distribution. However, in some scenarios with higher mean annual precipitation, manipulation of precipitation extremes caused annual precipitation distribution to change from left-skewed (skewness less than 0) to right-skewed (skewness more than 0). In the probability-based distribution scenarios, the precipitation extremes strongly controlled the skewness and kurtosis for the scenarios with lower MAPs (Figure 4c,d). The effect tended to be saturated for the scenarios with higher MAPs.

3.3. Response of Skewness–Kurtosis Interactions to Precipitation Extremes

Precipitation extremes had stronger effects on the interactions of the kurtosis and skewness of annual precipitation distribution for the meteorological stations at low altitudes (Figure 5a,b). The effect was positive for annual maximum daily precipitation, while the effect was negative for the number of dry days in a year. The response of the skewness–kurtosis interactions to precipitation extremes was the most sensitive for meteorological stations characterized as being in arid zones (Figure 5c,d). The effects of precipitation extremes on skewness–kurtosis interactions based on precipitation zoning were similar to those according to altitude.

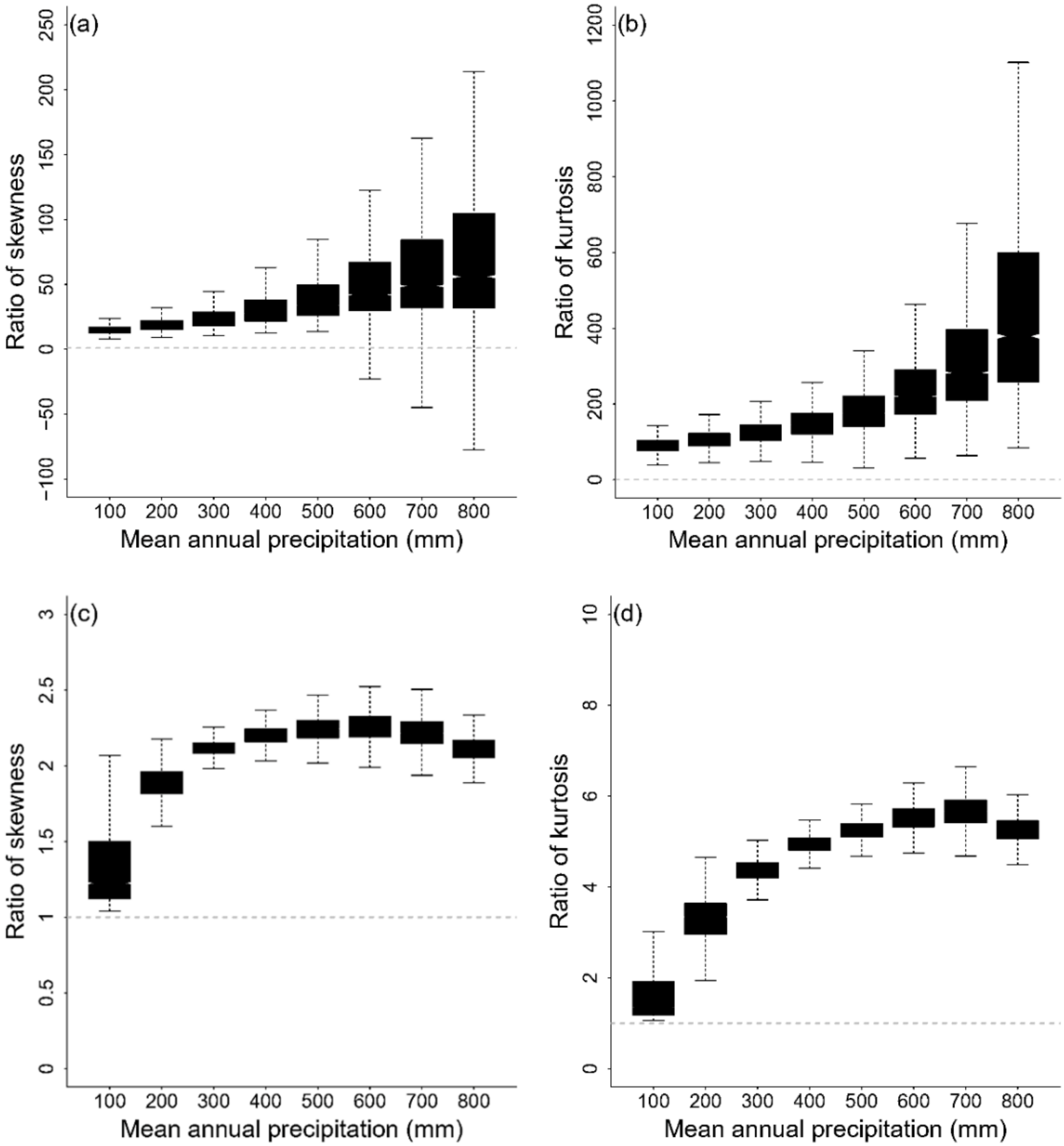

Figure 4. The ratio of high-order statistical parameters of annual precipitation distribution before and after daily precipitation manipulation along the gradient of mean annual precipitation. Normal distribution: skewness (**a**) and kurtosis (**b**); probability-based distribution: skewness (**c**) and kurtosis (**d**). The grey dashed line denotes a value of 1 for the vertical axis.

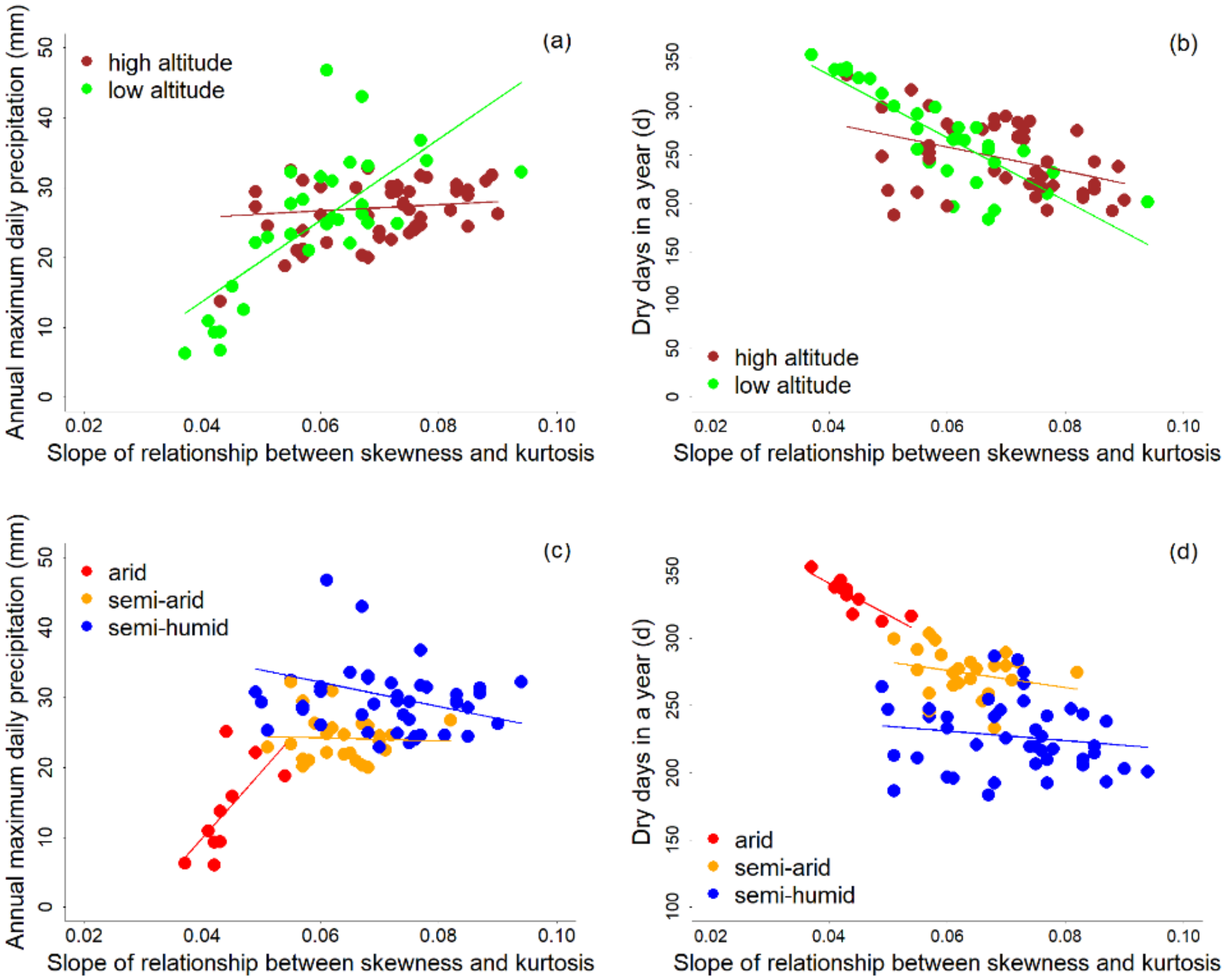

Figure 5. Effects of precipitation extremes on skewness–kurtosis interactions of annual precipitation distribution. Precipitation extremes were shown by two indices, namely annual maximum daily precipitation and the number of dry days in a year. The effects of both indices were assessed in terms of various altitudes (**a**,**b**) and climate zones (**c**,**d**).

4. Discussion

The results showed that the kurtosis of annual precipitation distribution on the Qinghai–Tibetan Plateau (QTP) was positively associated with the skewness. The skewness–kurtosis relationship (SKR) looked similar to that of plant trait distribution [22]. Both skewness and kurtosis are key statistical properties determining climate regimes and distributions, and can be considered indicator signals of climate extremes [23]. Positive values of skewness indicated that small precipitation amounts, such as 1 mm/day or less, dominated the whole year for these QTP ecosystems. Most areas on the QTP are characterized by arid or semi-arid biomes [24]. Very large values of kurtosis suggest that daily precipitation amount in a year is very unevenly distributed. This increases the occurrence probability of precipitation extremes. The direction and strength of the SKR usually change with environmental conditions, as suggested by Gross et al. [22]. I also found that the skewness of annual precipitation distribution responded to the kurtosis more strongly at high altitudes than at low ones. This suggests that high-order statistical parameters of annual precipitation distribution are more sensitive to climate change at high altitudes. Certainly, I am aware that this result may be site-dependent; the QTP, as the highest plateau in the world, is characterized by unique climate and ecosystem dynamics.

Increases of maximum daily precipitation and the number of dry days increased the skewness and kurtosis of annual precipitation distribution on the QTP. Li-Ge et al. [25] found that maximum daily rainfall and longest nonprecipitation period were closely related to potential changes in precipitation distribution. Several studies have shown that maximum daily precipitation is exhibiting a long-term increasing trend on the QTP [18,20,26], although the tendency is insignificant. The results showed that the promoting effects of precipitation extremes on skewness and kurtosis tended to be amplified with higher mean annual precipitation in normal distribution scenarios. These effects tended to be saturated for scenarios of higher mean annual precipitation in probability-based scenarios. Higher values of mean annual precipitation have been shown to correspond to higher intra- and interannual precipitation variabilities on the QTP [21]. Changes in these variabilities modulate the intensity and frequency of precipitation extremes [27,28]. The skewness and kurtosis of annual precipitation distribution can be considered indicators of precipitation extremes. These high-order statistical parameters partly test the reliability of the simulated precipitation extremes.

I further found that precipitation extremes strongly impacted skewness–kurtosis interactions at low altitudes and in arid zones. The amount of precipitation tended to be lower at low altitudes than at high ones on the QTP. That is, the effect of precipitation extremes on skewness–kurtosis interactions was largely determined by the regional aridity. The dynamics of dryness and moisture shape patterns of precipitation extremes [29]. At the global scale, precipitation extremes show obvious long-term increasing changes, while these changes are not robust in arid regions [30]. The above-mentioned results may remind us that when we simulate precipitation extremes, we should be mindful of the environmental conditions, climatic zones, and statistical distribution types of selected generated time-series precipitation data. This will greatly reduce the uncertainties of extreme precipitation simulations.

5. Conclusions

The results clearly show that precipitation extremes significantly alter the skewness, kurtosis, and skewness–kurtosis interactions of annual precipitation distribution on the Qinghai–Tibetan Plateau (QTP). These effects change with mean annual precipitation, geographical conditions, and ecosystem type. Examination of the relationship between precipitation extremes and the high-order statistical properties of precipitation distributions will allow us to better simulate the intensity and frequency of precipitation extremes in vegetation models. This further highlights the role of high-order statistical properties in studies of the complexity of precipitation extremes. Given the high climatic sensitivity of the QTP ecosystems and the increasing frequency of precipitation extremes, a comprehensive assessment of the key variables in the mapping of precipitation extremes is warranted.

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Conflicts of Interest: The author declares no conflict of interest.

Appendix A

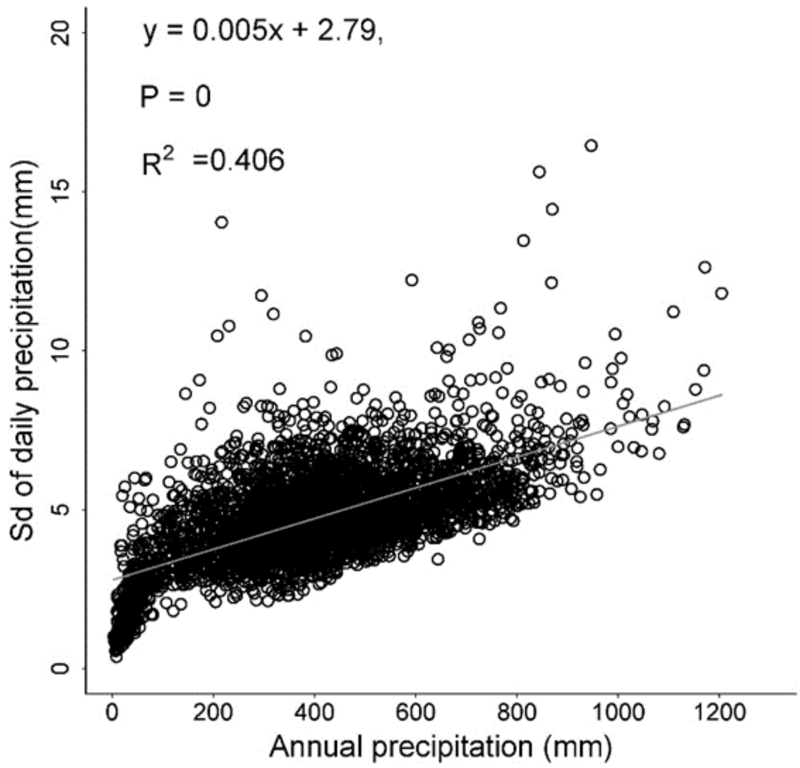

Figure A1. The relationship between annual precipitation and standard deviation (Sd) of daily precipitation in a year based on yearly data of 78 meteorological stations from 1960 to 2015 on the QTP.

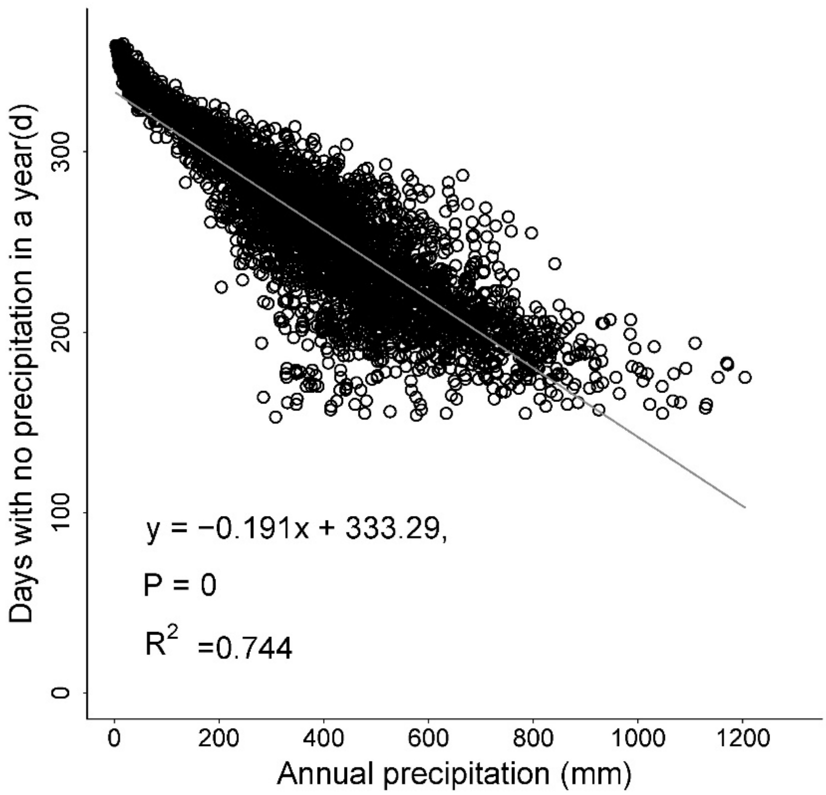

Figure A2. The relationship between annual precipitation and days with no precipitation in a year based on yearly data of 78 meteorological stations from 1960 to 2015 on the QTP.

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