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Long-Term Changes and Variability of Ecologically-Based Climate Indices along an Altitudinal Gradient on the Qinghai-Tibetan Plateau

Tong Guo

College of Urban and Environmental Sciences, Peking University, Beijing 100871, China; tongg@pku.edu.cn

Abstract: Extreme climate events are typically defined based on the statistical distributions of climatic variables; their ecological significance is often ignored. In this study, precipitation and temperature data from 78 weather stations spanning from 1960 to 2015 on the Qinghai-Tibetan Plateau were examined. Specifically, long-term and altitudinal variability in ecologically relevant climate indices and their seasonal differences was assessed. The results show that indices of daily temperatures greater than 10 °C and 25 °C show positive annual change trends during the growing season (May to September). Indices of daily rainfall greater than 2 mm, 3 mm and 5 mm positively alternate with years both in and around the growing season (May–September, April and October). In contrast, the index of daily snowfall greater than 2 mm shows opposite annual variability. Additionally, a higher altitude significantly leads to fewer days with temperature deviations above 20 °C, except for in October. The three abovementioned rainfall indices present significantly positive variability with increasing altitude during the growing season. In contrast, the snow index shows similar altitudinal changes in the months surrounding the growing season. This study allows us to better cope with the threats of climate change to vulnerable ecosystems.

Keywords: precipitation; temperature; climate-sensitive areas; ecological relevance; seasonal difference; Tibet

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1. Introduction

Spatiotemporal variability in climatic variables has long been a focus of climate research [1,2]. Global warming has led to a rapid change in the climate system and has thus altered spatiotemporal variability in climatic variables [3]. Anomalous or increased variability is likely to cause precipitation and temperature extremes [4,5]. Extreme precipitation and temperature events present increasing potentials, as projected by observations and model simulations [6,7].

However, current studies of extreme climate events have mostly concentrated on spatiotemporal variability in climatic variables defined using statistical distributions [8–10]. These conventional indices of extreme climate events, based on statistical definitions, only emphasize their rarity and ignore their associations with ecosystems [11]. The rarity of extreme climate events has been taken into account using the distributional tails depicted by percentile-based thresholds such as 10% or less [12]. Extreme climate events, when considered from a statistical perspective alone, may not necessarily cause extreme responses of ecosystems or strongly disturb ecosystems [13]. Thus, ecological information should be taken into account when examining climatic variables in particular ecosystem responses to extreme climate events [14]. It is well known that extreme climate events strongly impact the structure and functioning of ecosystems [15]. Ecosystem responses to extreme climate events are highly context-dependent and nonlinear [13]. In addition, extreme climate events are likely to cause instantaneous and dramatic changes in biological systems, such as pushing systems to tipping points (so-called threshold behaviors), owing to their strengths and short duration times [5]. These factors challenge a deeper understanding of the nature of extreme climate events in terms of ecosystem impacts.

To fill this knowledge gap, it is necessary to consider extreme climate events from an ecological perspective in addition to considering their statistical aspects. It is time to transfer the research focus from studying statistically based indices of extreme climate events to examining climatic variables with explicit ecological significances. That is, the consideration of climatic variables or even extreme climate events should be extended from both their influencing factors (their intensity or frequency) to and their responses (their ecological relevance) [16]. The thresholds derived from climatic variables with ecological relevance are different from those derived from statistically based indices of extreme climate events. Moreover, the values of these thresholds are generally low for climatic variables with ecological relevance. In arid and semiarid ecosystems, rainfall greater than 2 mm allows soil microbes to strongly reproduce in the growing season. Rainfall less than 3 mm leads to a failure or lower rates of plant carbon fixation [17,18]. The optimum air temperature for ecosystem-level gross primary productivity was estimated to be 23 $\pm$ 6 °C at the global average level [19]. Examining these thresholds of climatic variables with ecological significance allows us to better understand ecosystem responses to climate change, especially in regions with high climatic sensitivity.

Examinations of climatic variables are often conducted at an annual resolution [20–22]. However, the seasonality of climatic variables is likely to be more suitable than the annual trend for detecting ecosystem responses [23]. The characteristics of ecologically meaningful climatic variables differ greatly in various seasons [24]. Consequently, this leads to the annual change trend of climatic variables representing a neutralized outcome induced by seasonal differences. In addition, the growing season in a year plays an important role in modulating ecosystem variables. Precipitation and temperature during the growing season directly impact the hydrothermal conditions that are necessary for vegetation growth, soil water and nutrients.

This study assessed long-term and altitudinal variability in ecologically relevant indices based on precipitation and temperature on the Qinghai-Tibetan Plateau (QTP). The QTP alpine ecosystems are vulnerable and are susceptible to climate change. Alpine ecosystems are characterized by large areas of permafrost and snow. The increasing rate of annual mean temperature on the QTP is roughly twice the rate of global warming [3]. Warmth-related indices of temperature extremes show temporally significant increasing trends on the QTP. The increment of minimum temperature indices is larger than that of maximum temperature indices. Trends are generally statistically nonsignificant for the decadal-scale variability of extreme precipitation indices on the QTP. Most extreme precipitation indices exhibit an increasing variability in the southern and northern parts of QTP. In addition, changes in extreme precipitation indices of the QTP are often independent on the altitude [10,25–28]. In this study, the following questions were addressed. (1) How do precipitation and temperature indices with ecological relevance vary in the long-term period and along the altitude gradient? (2) What are the differences between the growing season and around the growing season for the variability in precipitation and temperature indices with ecological relevance?

2. Materials and Methods

2.1. Study Area

The Qinghai-Tibetan Plateau (QTP) is described as the "roof of the word" and has a mean altitude of more than 4000 m. The QTP covers an area of approximately 2.5 million km^2 [29]. The latitude and longitude of the QTP range from 26°00′ to 39°47′ N and from 73°19′ to 104°47′ E, respectively. The QTP is considered a climate promoter of the Northern Hemisphere [30]. The QTP alters the regional atmospheric circulation by blocking westerly flows and the formation of Indian monsoons. Thus, the QTP strongly impacts regional precipitation and temperature distributions and even the global climate system. A cold and arid climate dominates the QTP, with mean annual temperatures ranging from −3.1 to 4.4 °C and mean annual precipitation totals ranging from 103 to 694 mm [31].

The QTP is characterized by alpine ecosystems. The ecosystems on the QTP are rather vulnerable to climate change owing to their unique climatic conditions. Grasslands cover over 60% of the area of the QTP [32]. Alpine steppes, alpine meadows and desert steppes constitute the grassland landscapes of the QTP. These landscapes are an important source of human activities and livestock grazing. The grassland land cover type gradually turns green at the end of April or at the beginning of May. The vegetation biomass reaches its peak in the middle of August [33].

2.2. Data

This study used data from the Qinghai and Tibet provinces to analyze spatiotemporal variability in precipitation and temperature variables. There are 39 weather stations in each region and 78 weather stations (or sites) total (Figure 1). Geographical information was obtained for the weather station, including the latitude, longitude and altitude of each station (see Table 1). Daily observed precipitation and temperature data were collected during the period from 1960 to 2015 from the website of the National Meteorological Information Center (http://data.cma.cn). As the data periods are not consistent among the stations, I assessed the data based on three principles. (1) An analysis of climatic changes in a specific region often requires data records comprising no fewer than 30 years. However, thirteen weather stations were established after the 1990s on the QTP (Figure 1). The weather stations that were included covered 25 years of weather records. In addition, three weather stations had data records spanning fewer than 20 years; these data were removed from the analysis. Thus, 75 weather stations were selected for use in the assessment of long-term and altitudinal variability in climate indices throughout the study. (2) The percentage of missing data in each year should not go beyond 10% of the data of the whole year, and the missing data are not included in the examination. All weather stations have missing values of precipitation but none of temperature (see Table 1). However, the average missing ratio of precipitation on the annual scale is lower than 0.5% for all the weather stations. This annual missing ratio of precipitation is rather low, indicating a relatively high continuity of data and a reliability of data analysis. In addition, all the selected stations have fixed geographical locations to guarantee the temporal continuity and reliability of the weather data. All the stations were further separated into different climatic zones based on their annual precipitation and temperature conditions [29]. The zoning scheme using measurements of temperature strength (TS) is depicted by the average value of the warmest month in a year, including cold (TS: < 10 °C), warm (TS: 10–18 °C) and hot (TS: > 18 °C) zones. The selected stations (75) were separated into 5 hot sites, 42 warm sites and 28 cold sites based on the temperature zoning scheme. The rule regulating the zoning of moisture relies on the mean annual precipitation (MAP) index and includes arid (MAP: 0–200 mm), semiarid (MAP: 200–400 mm), semihumid (MAP: 400–800 mm) and humid (MAP: > 800 mm) zones. Based on the precipitation zoning scheme, the selected stations were categorized into 10 arid areas, 23 semiarid areas, 41 semihumid areas and only one humid area.

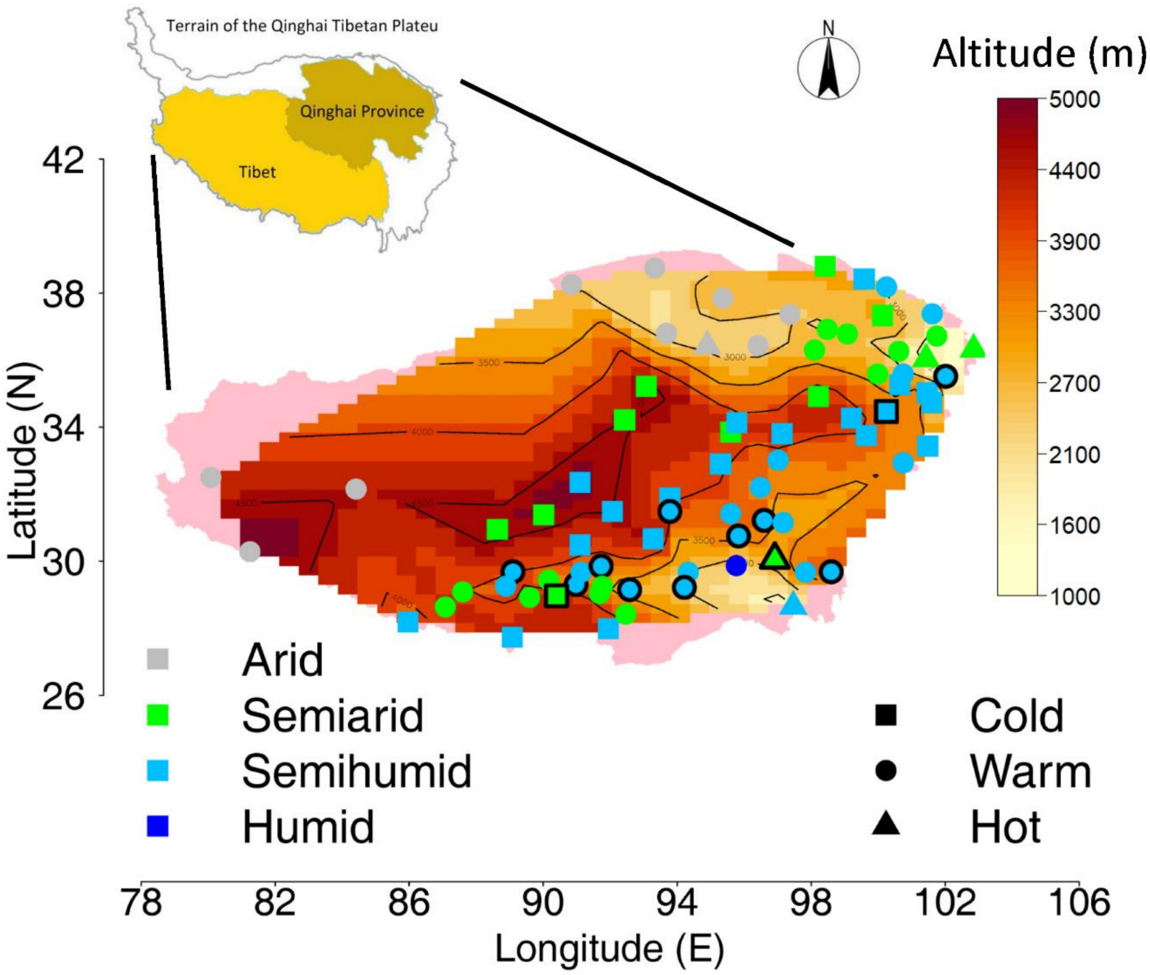

Figure 1. Locations, climate zones and altitudes of 78 weather stations on the Qinghai-Tibetan Plateau. The 13 weather stations established after the 1990s are marked with black borders.

Table 1. Location and altitude of each weather station and their corresponding climatic zones. Missing ratio of time series data was calculated separately for precipitation and temperature.

Sites	Latitude (°N)	Longitude (°E)	Altitude (m)	Precipitation Zoning	Temperature Zoning	Missing Ratio (%)	
						P	T
Anduo	32.35	91.1	4800	Semihumid	Cold	0.19	0
Bange	31.38	90.02	4700	Semiarid	Cold	0.2	0
Banma	32.93	100.75	3530	Semihumid	Warm	0.19	0
Basu	30.05	96.92	3260	Semiarid	Hot	0.09	0
Biru	31.48	93.78	3940	Semihumid	Warm	0.09	0
Bomi	29.87	95.77	2736	Humid	Warm	0.21	0
Chaka	36.78	99.08	3088	Semiarid	Warm	0.15	0
Changdu	31.15	97.17	3306	Semihumid	Warm	0.21	0
Chayu	28.65	97.47	2328	Semihumid	Hot	0.17	0
Cuona	27.98	91.95	4280	Semihumid	Cold	0.18	0
Dachaidan	37.85	95.37	3173	Arid	Warm	0.21	0
Dangxiong	30.48	91.1	4200	Semihumid	Cold	0.2	0
Dari	33.75	99.65	3968	Semihumid	Cold	0.21	0
Delingha	37.37	97.37	2982	Arid	Warm	0.21	0
Dingqing	31.42	95.6	3873	Semihumid	Warm	0.2	0
Dingri	28.63	87.08	4300	Semiarid	Warm	0.2	0

Table 1. *Cont.*

Sites	Latitude (°N)	Longitude (°E)	Altitude (m)	Precipitation Zoning	Temperature Zoning	Missing Ratio (%)	
						P	T
Dulan	36.3	98.1	3191	Semiarid	Warm	0.21	0
Gaize	32.15	84.42	4415	Arid	Warm	0.16	0
Gangcha	37.33	100.13	3302	Semiarid	Cold	0.21	0
Geermu	36.42	94.9	2808	Arid	Hot	0.21	0
Gongga	29.3	90.98	3555	Semihumid	Warm	0.09	0
Guinan	35.58	100.75	3120	Semihumid	Warm	0.06	0
Guizhou	36.03	101.43	2237	Semiarid	Hot	0.21	0
Guoluo	34.47	100.25	3719	Semihumid	Cold	0.09	0
Henan	34.73	101.6	3500	Semihumid	Cold	0.21	0
Jiacha	29.15	92.58	3260	Semihumid	Warm	0.09	0
Jiali	30.67	93.28	4489	Semihumid	Cold	0.21	0
Jiangzi	28.92	89.6	4040	Semiarid	Warm	0.21	0
Jiuzhi	33.43	101.48	3629	Semihumid	Cold	0.2	0
Langkazi	28.97	90.4	4432	Semiarid	Cold	0.09	0
Lasa	29.67	91.13	3649	Semihumid	Warm	0.21	0
Lazi	29.08	87.6	4000	Semiarid	Warm	0.14	0
Leiwuqi	31.22	96.6	3810	Semihumid	Warm	0.09	0
Lenghu	38.75	93.33	2770	Arid	Warm	0.21	0
Linzhi	29.67	94.33	2992	Semihumid	Warm	0.21	0
Longzi	28.42	92.47	3860	Semiarid	Warm	0.21	0
Luolong	30.75	95.83	3640	Semihumid	Warm	0.09	0
Maduo	34.92	98.22	4272	Semiarid	Cold	0.21	0
Mangkang	29.68	98.6	3870	Semihumid	Warm	0.09	0
Mangya	38.25	90.85	2945	Arid	Warm	0.21	0
Menyuan	37.38	101.62	2850	Semihumid	Warm	0.21	0
Milin	29.22	94.22	2950	Semihumid	Warm	0.09	0
Minhe	36.32	102.85	1814	Semiarid	Hot	0.21	0
Mozhugongka	29.85	91.73	3804	Semihumid	Warm	0.09	0
Nangqian	32.2	96.48	3644	Semihumid	Warm	0.21	0
Nanmulin	29.68	89.1	4000	Semihumid	Warm	0.09	0
Naqu	31.48	92.07	4507	Semihumid	Cold	0.21	0
Nielaer	28.18	85.97	3810	Semihumid	Cold	0.18	0
Nimu	29.43	90.17	3809	Semiarid	Warm	0.16	0
Nuomuhong	36.43	96.42	2790	Arid	Warm	0.21	0
Pali	27.73	89.08	4300	Semihumid	Cold	0.21	0
Pulan	30.28	81.25	4900	Arid	Warm	0.16	0
Qiabuqia	36.27	100.62	2835	Semiarid	Warm	0.21	0
Qilian	38.18	100.25	2787	Semihumid	Warm	0.21	0
Qingshuihe	33.8	97.13	4415	Semihumid	Cold	0.21	0
Qiongjie	29.03	91.68	3741	Semiarid	Warm	0.04	0
Qumalai	34.13	95.78	4175	Semihumid	Cold	0.2	0
Rikaze	29.25	88.88	3836	Semihumid	Warm	0.21	0
Shenzha	30.95	88.63	4672	Semiarid	Cold	0.21	0
Shiquanhe	32.5	80.08	4279	Arid	Warm	0.21	0
Suoxian	31.88	93.78	4023	Semihumid	Cold	0.21	0
Tongde	35.27	100.65	3289	Semihumid	Cold	0.15	0
Tongren	35.52	102.02	2491	Semihumid	Warm	0.09	0
Tuole	38.8	98.42	3367	Semiarid	Cold	0.21	0
Tuotuohe	34.22	92.43	4533	Semiarid	Cold	0.21	0
Wudaoliang	35.22	93.08	4612	Semiarid	Cold	0.21	0
Wulan	36.92	98.48	2950	Semiarid	Warm	0.06	0
Xiaozaohuo	36.8	93.68	2767	Arid	Warm	0.2	0
Xinghai	35.58	99.98	3323	Semiarid	Warm	0.21	0
Xining	36.72	101.75	2295	Semiarid	Warm	0.21	0
Yeniugou	38.42	99.58	3320	Semihumid	Cold	0.21	0

Table 1. *Cont.*

Sites	Latitude (°N)	Longitude (°E)	Altitude (m)	Precipitation Zoning	Temperature Zoning	Missing Ratio (%)	
						P	T
Yushu	33.02	97.02	3681	Semihumid	Warm	0.21	0
Zaduo	32.9	95.3	4066	Semihumid	Cold	0.21	0
Zedang	29.25	91.77	3552	Semiarid	Warm	0.21	0
Zeku	35.03	101.47	3663	Semihumid	Cold	0.12	0
Zhiduo	33.85	95.6	4179	Semiarid	Cold	0.09	0
Zhongxinzhan	34.27	99.2	4211	Semihumid	Cold	0.14	0
Zuogong	29.67	97.83	3780	Semihumid	Warm	0.14	0

2.3. *Climate Metric Indices with Ecological Relevance*

Climate variables stemming from ecological considerations are the focus of this study (Figure 2). These variables compose the basis for understanding climate scenarios causing extreme ecological responses. For example, the optimal temperature for plant photosynthesis is 25 °C in a given region. In contrast, the temperature of an extreme event may reach 35 °C based on a statistical probability calculation, such as the 95th percentile. The threshold of extreme temperature events is thus much larger than that of the temperature index with ecological relevance. That is, the temperature of 35 °C is extreme for plant photosynthesis. Certainly, the thresholds of extreme climate events can also be smaller than those of climate indices based on ecosystem variables. That is, these extreme climate events do not cause extreme responses in ecosystems. This study defined a set of climate metric indices with ecological relevance, as listed below (Table 2). These indices are mostly based on the threshold behaviors of ecosystem variables responding to precipitation and temperature regimes or even extremes. The daily maximums or minimums of the climatic variables were not used as the standards with which to define indices with ecological relevance. Representative variables were selected from different ecosystem components, such as vegetation, soil and microorganisms, and considered main ecosystem processes, such as water and carbon cycling, based on limited references (Table 2). The behaviors were taken into account in an instantaneous response rather than a long-term accumulated response or a lagged manner response. Temperature strength- and snow intensity-regulating ecosystem components have been studied on the QTP [29,34,35]. However, little research has been performed on rainfall pulses triggering ecosystem variables on the QTP. Instead, precipitation indices with ecological relevance were defined based on related studies of rainfall pulses in other arid and semiarid grassland ecosystems [18,36]. Humid ecosystems are assumed to be weakly constrained by water availability compared to arid ecosystems. For all the climatic zones, the same standards were used for the climate indices with ecological relevance, owing to few comparative and systematic studies on the responses of different ecosystem types to the respective climatic variables on the QTP. Spatiotemporal variability in climate indices with ecological relevance was examined in two aspects: long-term changes (time scale: 1960–2015) and changes along the altitudinal gradient (range: 1814 m–4900 m). High-altitude areas are often characterized by rather low temperatures and very reduced precipitation in the nongrowing season, which leads to rather slow ecosystem process turnover rates. This is especially true during the months from November of a given year to February of the next year. During this time, evapotranspiration is quite small, and vegetation growth is assumed to cease. Moreover, alpine ecosystems on the QTP are mainly constrained by hydrothermal conditions. Changes in hydrothermal conditions mainly occur during the growing season. The dynamics of ecosystem components such as vegetation or soil are largely modulated by climatic variables during the growing season. Thus, the growing season is usually considered as an entirety and is used to mirror the continuity of climate effects on alpine ecosystems. Thus, long-term and altitudinal variability in climate indices with ecological relevance was specified in and around the growing season: during the growing season (May to September), during the one month before the growing season (April) and during the one month after the growing season (October). Several indices were exclusively calculated in specific seasons, e.g., days in which the temperature was less than 0 °C in April and in October. To better demonstrate the seasonal differences in the climate variables, the mean monthly precipitation and temperature values were calculated across the climatic zones (see Appendix A Figures A1 and A2).

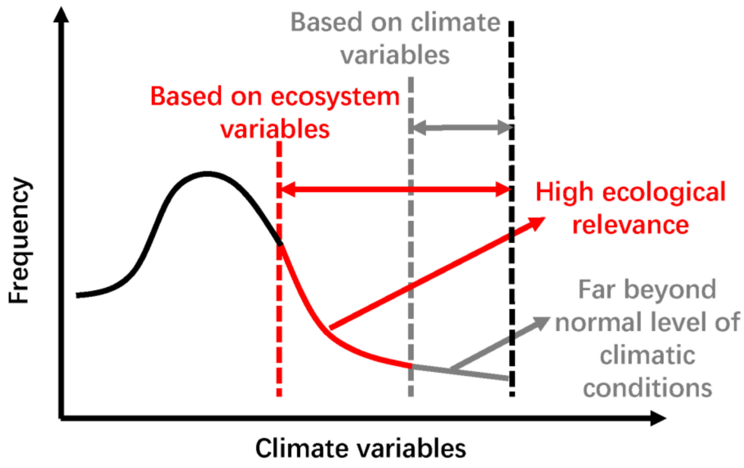

Figure 2. Definitions of climate metric indices with ecological relevance and indices of extreme climate events based on climatic variables. The ranges of climate indices are constrained in the parts of the graph between the dashed lines. The conventional indices of extreme climate events have often been identified as far beyond the normal levels of the climate conditions, corresponding to distributional tails of climatic variables (10% or less). The climate indices with ecological relevance refer to the magnitudes of the climatic variables that cause dramatic changes (threshold behaviors) in the ecosystem variables. For the climate indices with ecological relevance, their distributions can also be narrower than those of the conventional indices of extreme climate events. The case in which sampling points constrained by climate indices with ecological relevance was not particularly demonstrated since these sampling points are also captured by conventional indices of extreme climate events. The distance between the red and gray dashed lines varies with different ecosystem variables and climatic variables. In this study, climate variables mainly refer to daily precipitation and temperature. Ecosystem variables were considered from different ecosystem components like vegetation and soil, and important processes like water and carbon cycle.

Table 2. Temperature and precipitation metric indices with ecological relevance.

Climate Factors	Index Description	Ecological Relevance	Unit	Season
Temperature	Daily temperature higher than 25 °C (DTH25)	The optimum temperature of alpine vegetation photosynthesis is assumed to be 25 °C on the Plateau [34].	Day	Grow
	Daily temperature higher than 10 °C (DTH10)	Days of daily temperature above 10 °C is related to the duration of the fast-growing season on the Plateau [29].	Day	Grow
	Daily temperature lower than 3 °C (DTL3)	Decomposition activities of soil microorganisms nearly stop below 3 °C on the Plateau [34].	Day	Apr/Oct
	Daily temperature lower than 0 °C (DTL0)	Available (or "effective") soil water is assumed to be zero. Water turns into the frozen state which cannot be utilized by plants.	Day	Apr/Oct
	Daily temperature deviation more than 20 °C (DTDH20)	Daytime temperature (25 °C) related to vegetation photosynthesis minus night temperature ($\geq$ 5 °C) related to the normal growth of alpine plants [29].	Day	All

Table 2. *Cont.*

Climate Factors	Index Description	Ecological Relevance	Unit	Season
Precipitation	Daily rainfall more than 2 mm (DRH2)	A summer rain event of 2 mm stimulates the activity of soil microbes in arid or semiarid ecosystems [18].	Day	All
	Daily rainfall more than 3 mm (DRH3)	Summer rain events of at least 3 mm are often necessary to elevate rates of carbon fixation in arid or semiarid ecosystems [18].	Day	All
	Daily rainfall more than 5 mm (DRH5)	Rain events above 5 mm can effectively supplement the water of root layers in arid or semiarid ecosystems [36]. Net CO_2 absorption rate rises to maximum values after 3 consecutive days of 5-mm rainfall pulses in water-limited ecosystems [37].	Day	All
	Daily snow more than 2 mm (SnowH2)	Snow events above 2 mm (extreme snow) significantly alter the distribution of water and energy on the Plateau [35].	Day	All

Note: For the column "Season", "All" means the indices were analyzed in all three seasons; "Grow' means the indices were analyzed only in the growing season; "Apr/Oct" means the indices were analyzed only in April and in October (around the growing season).

2.4. Statistical Analysis of Climatic Variables with Ecological Relevance

The Mann-Kendall nonparameter test is generally used to assess the temporal trend of a time-series variable [38]. Thus, this method was used to analyze the annual variability in the climate variables. Nonparametric trend detection methods are less sensitive to outliers than parametric methods are. The description of the M-K test is given below (Equations (1)–(4)). Time series data are usually affected by serial correlation. To minimize the effects of autocorrelation on the trend detection analysis, I used the modified Mann-Kendall test of Yue and Wang [39]. The stations with significant temporal variability in these climate indices were further integrated into climatic zones. A linear regression model is used to test the linear relationship between two variables. This method was used to identify the change trend (slope), the fitting degree (R squared) and the significance (p value) of the climatic variables along the altitude gradient (Equation (5)). All of the abovementioned methods were performed in the version 3.6.3 of R software [40].

Mann-Kendall nonparameter test:

For the time-series variable $X = (x_1, x_2, \ldots, x_n)$, n is the length of the variable. S is a variable that is defined as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \tag{1}$$

where x_i and x_j in Equation (1) refer to the observed values of climate indices in year i and j, respectively. The Sgn function is used to judge the sign of the equation.

$$Sgn(x_j > x_i) = \begin{cases} 1 & x_j > x_i \\ 0 & x_j = x_i \\ -1 & x_j < x_i \end{cases} \tag{2}$$

In the case that $n > 8$, the random time-series variable $S_i (i = 1, 2, \ldots, n)$ is assumed to obey the normal distribution. The variance is given as follows:

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{k=1}^{n} k(k-1)(2k+5)}{18} \tag{3}$$

The variable S was standardized, and the variable Z_{MK} was obtained.

$$Z_{MK} = \begin{cases} (S-1)/\sqrt{Var(S)} & S > 0 \\ 0 & S = 0 \\ (S+1)/\sqrt{Var(S)} & S < 0 \end{cases} \tag{4}$$

In Equation (4), when $Z_{MK} > 0$, the time series variable X shows an increasing trend, while the variable X shows a decreasing trend in the case that $Z_{MK} < 0$.

In the linear fitting model, altitude was deemed an independent variable. Each climate index was deemed a dependent variable. The altitudinal variability in the climate indices was analyzed based on the multiyear mean values of each weather station.

$$Slope = \frac{n \times \sum_{i=1}^{n}(x_i \times y_i) - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{n \times \sum_{i=1}^{n} {x_i}^2 - \left(\sum_{i=1}^{n} x_i\right)^2} \quad (5)$$

In the above equation, the slope indicates the change trend of the fitted lines; y_i denotes the observed value of the climate indices at site i; x_i denotes the altitude value at site i; and n is the total number of sites (or weather stations) in the Qinghai and Tibet provinces. The significance level of all statistical analyses is $p < 0.05$.

3. Results

3.1. Long-term Variability in Precipitation and Temperature Variables with Ecological Relevance

The temperature metric indices DTL0 and DTL3 showed decreasing long-term trends around the growing season (Figure 3). The indices DTH10 and DTH25 temporally increased during the growing season; moreover, the varying extents of both indices were much greater than those of DTL0 and DTL3. For the DTDH20 index, negative variability seemed to be slightly strong in April. Nevertheless, positive variability dominated in the growing season and in October.

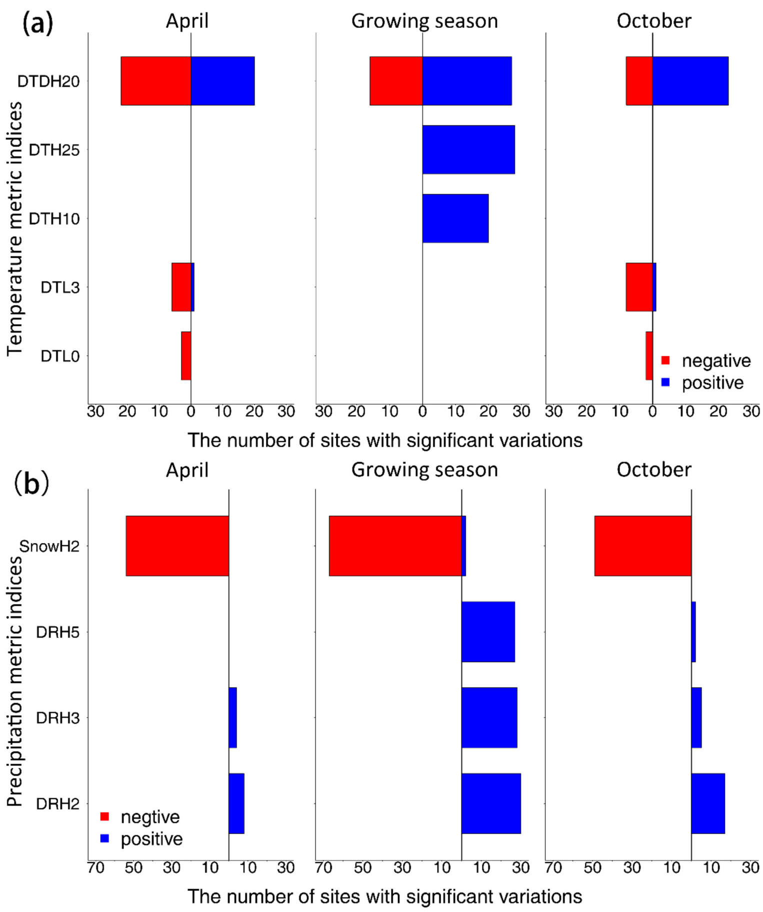

Figure 3. The number of stations with significant annual variability in the temperature (**a**) and precipitation (**b**) metric indices with ecological relevance.

The rainfall metric indices DRH2, DRH3 and DRH5 presented increasing alternations at the annual scale for the three seasons. This alternation was stronger during the growing season than in the months surrounding it. In contrast, the SnowH2 index strongly decreased at the annual scale in and around the growing season.

3.2. Distributions of the Precipitation and Temperature Variables with Ecological Relevance across Climatic Zones

DTL0, DTL3, and DTH10, the temperature metric indices with significant annual variability, all occurred at cold and warm sites (Table 3). The hot climatic zones hosted higher probabilities of occurrence for the DTH25 index. The index DTDH20 reached peak values in the warm climatic zones regardless of season.

Table 3. Percentages (%) of stations with significant annual variability (based on the M-K test) in the temperature metric indices with ecological relevance across the climatic zones. The character "C" denotes cold areas; "W" denotes warm areas; "H" denotes hot areas; and "–" means no analysis of this index was conducted during the given seasons.

Index	April			Growing Season			October		
	C	W	H	C	W	H	C	W	H
DTL0	7.1	2.4	0.0	–	–	–	3.6	2.4	0.0
DTL3	7.1	11.9	0.0	–	–	–	17.9	9.5	0.0
DTH10	–	–	–	46.4	16.7	0.0	–	–	–
DTH25	–	–	–	0	57.1	80.0	–	–	–
DTDH20	25.0	78.6	40.0	21.4	81.0	60.0	7.1	66.7	20.0

Rainfall metric indices with significant annual variability had higher probabilities of occurrence in the semiarid and semihumid climatic zones except for the DRH2 index (Table 4). However, this index was observed in the only humid site in and around the growing season. The occurrence of heavy snow tended to be quite high across the precipitation-based climatic zones.

Table 4. Percentages (%) of stations with significant annual variability in the precipitation metric indices with ecological relevance across the climatic zones. The character "A" denotes arid areas; "SA" denotes semiarid areas; "SH" denotes semihumid areas; "H" denotes humid areas; and "/" means no analysis of this index was conducted during the given seasons.

Index	April				Growing Season				October			
	A	SA	SH	H	A	SA	SH	H	A	SA	SH	H
DRH2	0.0	4.3	14.6	100.0	20.0	43.5	41.5	100.0	0.0	0.0	39.0	100.0
DRH3	0.0	0.0	9.8	0.0	30.0	43.5	36.6	0.0	0.0	0.0	12.2	0.0
DRH5	0.0	0.0	0.0	0.0	20.0	43.5	36.6	0.0	0.0	0.0	4.9	0.0
SnowH2	70.0	78.3	68.3	100.0	90.0	87.0	97.6	0.0	60.0	69.6	65.9	0.0

3.3. Changes in the Precipitation and Temperature Variables with Ecological Relevance Along the Altitudinal Gradient

The temperature metric index DTL0 significantly increased with increasing altitude around the growing season. In contrast, high altitudes led to a marked reduction in the DTH25 index in the growing season (Table 5). The indices DTL3 and DTH10 did not show significant variability along the altitude gradient. Lower altitudes were beneficial for the formation of a greater temperature deviation (DTDH20) in April and during the growing season, while this effect was rather weak in October.

Table 5. Variability in the precipitation and temperature metric indices with ecological relevance along the altitude gradient. The change trends and coefficients of the linear fitting model are shown with a significance level of $p < 0.05$. The sign "↓" means a significant decrease; "↑" means a significant increase; "Null" means no significant change; and "–" means no analysis of the index was conducted during the given seasons.

Climate Variables	Index	Growing Season					
		Trend	*p*	Trend	*p*	Trend	*p*
Temperature	DTL0	↑	0.007	–	–	↑	0.010
	DTL3	Null	0.106	–	–	Null	0.109
	DTH10	–	–	Null	0.387	–	–
	DTH25	–	–	↓	0.027	–	–
	DTDH20	↓	0.007	↓	0.002	Null	0.062
Precipitation	DRH2	Null	0.459	↑	0.001	Null	0.582
	DRH3	Null	0.417	↑	0.001	Null	0.504
	DRH5	Null	0.369	↑	0.001	Null	0.263
	SnowH2	↑	0	Null	0.870	↑	0

The rainfall metric indices with ecological relevance showed significantly positive variability with increasing altitude in the growing season. Nevertheless, the variability did not occur around the growing season. The SnowH2 index was positively altered at a high altitude around the growing season, while altitude had a weak impact on heavy snow alterations during the growing season.

4. Discussion

Conventional indices of extreme climate events based on climatic variables were defined according to absolute or relative values derived from statistical curves. These indices are influenced by the distribution of weather data. The climate metric indices with ecological relevance are based on ecosystem responses to climatic variables since the responses often correspond to specific thresholds or ranges [41]. Thus, this study defined a set of climate indices with ecological relevance characterized by alpine ecosystems on the Qinghai-Tibetan Plateau (QTP). Specifically, these indices include five temperature metric indices and four precipitation metric indices that are closely linked to corresponding ecosystem variables.

4.1. Long-Term Variability in Climatic Variables with Ecological Relevance

The results show that the indices of daily temperatures lower than 0 °C (DTL0) and 3 °C (DTL3) show long-term negative variability. In contrast, the indices of daily temperatures higher than 10 °C (DTH10) and 25 °C (DTH25) positively vary at the annual scale. This is the consequence of an increased temperature on the QTP. The rate of increase in the temperature on the QTP was 0.3–0.4 °C per decade during the study period, which was twice the global level in the past 60 years [3]. Moreover, enhanced greenhouse gas emissions induced by anthropogenic activities and low-level cloud amounts aggravated the temperature increase in QTP ecosystems [42]. The varying degrees of DTH10 and DTH25 are greater than those of DTL0 and DTL3. This suggests that various ecosystem variables responding to increasing temperature may not present consistent variance rates. Ecosystem variables might also engage in feedback systems with each other, owing to their distinctive response sensitivities to climatic variables [43]. The results show that the index of daily temperature deviation higher than 20 °C (DTDH20) shows positive annual variability in the growing season and in October. In contrast, Ning [26] found a significant temporal decrease in the diurnal temperature range based on annual mean values in the Hengduan Mountains of the QTP. This highlights the necessity of examining long-term changes in temperature regimes in terms of seasonal differences. This result indicates longer times for the survival of plants in contexts with large temperature deviations. Large daily temperature deviations are assumed to not be beneficial for the growth of alpine plants on the QTP, since plants may need to invest more energy to resist great temperature changes. In addition, the result show that negative variability in the DTDH20 index seems to be slightly strong in April. This might be attributed to asymmetrical increments between daytime and nighttime temperatures, especially a greater increasing rate of temperature at night and in winter on the QTP [44,45]. The effects of daily temperature deviation on vegetation greenness differed between the period during and before the growing season on the QTP [46].

The results show that the indices of daily rainfall higher than 2 mm (DRH2), 3 mm (DRH3) and 5 mm (DRH5) positively alternate at the annual scale regardless of season. This finding is in line with the wetting trend on the QTP [27,28]. In addition, the varying extents of these rainfall indices are greater than those in the months surrounding the growing season. Moist soil conditions promote the growth of soil microorganisms and vegetation during the growing season. The effects of summer extreme precipitation amounts reached soil depths up to 105 cm on the QTP [47]. The result show that the index of daily snow greater than 2 mm (SnowH2) significantly decreases at the annual scale. This is consistent with previous findings regarding the shrinking snow cover on the QTP [48]. Increased snow promoted the early flowering of shallow-rooted plants in Tibet, as snowmelt increased the soil moisture of the upper layer [49]. Additionally, the results show that the long-term decreasing extent of SnowH2 is much stronger than the increasing extent of the extreme rainfall indices.

The Koppen-Geiger climate classification is a classical method of climate zonation considering precipitation, temperature and vegetation [50]. This study used the method outlined by Zheng [29]. The method is based on hydrothermal conditions and vegetation characteristics on the QTP. This method can be deemed an updated regional version of the Koppen-Geiger climate classification. The results show that temperature metric indices with significant annual variability often occur in cold and warm climatic zones rather than in hot ones. Ecosystem variables such as plant phenology or processes such as soil respiration are likely to be more sensitive to increased temperatures in colder sites than in warmer sites [51,52]. In addition, the result show that semiarid and semihumid zones generally capture precipitation metric indices with ecological relevance. The drought sensitivity of ecosystems reaches a peak in semiarid zones across various climate regimes [53]. In this study, the climate indices with ecological relevance were examined at the station-based level along the climatic gradient. The lower spatial resolution of this level may not sufficiently capture the variability in ecologically meaningful climate indices. Interpolated climate surfaces are an efficient method that can be used to fill this gap, particularly in regions with sparse data [54], such as the western part of Tibet.

4.2. Altitudinal Variability in Climatic Variables with Ecological Relevance

The results show that the temperature metric index DTL0 significantly decreases and the index DTH25 markedly increases along the altitude gradient. High altitudes are characterized by low temperatures. The temperature index DTDH20 shows a decreasing trend with increasing altitude in April and during the growing season. This indicates fewer days with large daily temperatures at high altitudes. The increasing rate of the temperature was quite different for altitudes below 4800 m on the QTP [55]. Moreover, the increasing temperature degree was largely dependent on the altitude of the QTP based on the climate simulations [56]. The results indicate that all precipitation metric indices show significantly positive variability along the altitude gradient. Specifically, the rainfall indices positively vary with increasing altitudes in but not around the growing season. Ge [10] found that the variability in extreme precipitation was not dependent on altitude on the QTP. Additionally, the results show that the seasonal distributions of the rainfall metric indices with ecological relevance are opposite to the altitudinal variability in the SnowH2 index.

Alpine ecosystems are largely constrained by hydrothermal conditions on the QTP [33]. In this study, indices that integrate precipitation and temperature variables with ecological relevance were not examined. This may partly constrain the ecological significance evolved from the results. However, the interactions between the daily precipitation values and daily mean temperatures were assessed in this study. The result show that days with temperatures greater than 5 °C account for 72% of all precipitation days (see Appendix A Figure A3). In addition, days with this suitable temperature (>5 °C) are often accompanied by precipitation ranging from 1 to 5 mm (see Appendix A Figure A4).

4.3. Necessity of Simulating Climatic Variables with Ecological Relevance in Ecosystem Models

Increased extremeness of future climates has been reported, including increases in extremely high temperatures, drought and exceptional rainfall [53,57]. Ecologists have perceived the severity of extreme climate events as they affect ecosystem variables and processes and have manipulated precipitation and temperature variables to assess the ecological implications of their abnormal variabilities [58–60]. However, these manipulations have often been restricted by the temporal scale. The response time of ecosystem variables often did not match the short-term manipulations of climatic variables [13]. For example, empirical studies found that observations of short-term experimental warming contradicted long-term investigations of alpine tundra phenology [61,62]. In addition, experimental manipulations of one climate factor may alter environmental conditions other than the controlled factor alone. These unexpected side effects on ecosystem processes are difficult to quantify [63]. In this study, the climate metric indices with ecological relevance were defined based on the limited reference results of in situ field work or in-lab experiments. The limited results constrained a direct analysis of the relationship between climatic variables or extreme climate events and ecosystem variables, either at long time series or at various spatial dimensions. Thus, the thresholds of climate indices with ecological relevance were not differentiated according to various ecosystem types on the Qinghai-Tibetan Plateau. Ecosystem models, together with remote sensing, may pave the way for a more reasonable definition of climate metric indices with ecological relevance. This may weaken the uncertainties caused by the differences of the responses of ecosystem variables to climatic variables among different sites. Simulated scenarios of extreme precipitation and temperature events in ecosystem models so far have failed to adequately capture the real extremeness of these climatic variables [11]. Moreover, ecosystem variables could also provide feedback on the intensity or frequency of extreme climate events such as drought intensification [64]. Thus, simulations of climatic variables with ecological relevance are necessary to address threats of future climate change and to predict their effects on vulnerable ecosystems [65]. In addition, the linkage of extreme climate events with climate change scenarios is necessary in future studies. This link will allow us to understand how climate means or variability affects extreme climate events. This will also largely fill the knowledge gap regarding the interactions between climate change, extreme climate events and ecosystem responses.

5. Conclusions

The Qinghai-Tibetan Plateau is very sensitive to climate change and its ecosystems are vulnerable. This study investigated long-term and altitudinal changes in ecologically-based climate indices based on time-series data from the year 1960 to 2015 of 78 weather stations in Qinghai and Tibet Provinces. The Mann-Kendall trend test and linear regression model were used to examine the spatio-temporal variability of these climate indices. The main findings are indices of daily temperatures greater than 10 °C and 25 °C show positive annual change trends during the growing season (May to September). Indices of daily rainfall greater than 2 mm, 3 mm and 5 mm positively alternate with years both in and around the growing season (May–September, April and October). In contrast, the index of daily snowfall greater than 2 mm shows opposite annual variability. The index of daily temperature lower than 0 °C exhibits significantly positive variability with increasing altitude around the growing season. In contrast, the index of daily temperature greater than 25 °C shows opposite altitudinal changes during the growing season. All precipitation indices with ecological relevance present significantly positive variability with increasing altitude.

Long-term and altitudinal variability in precipitation and temperature indices with ecological relevance indicates spatiotemporal changes in the hydrothermal conditions of alpine ecosystems on the QTP. Moreover, the seasonal differences observed in the variability in climate indices with ecological relevance allow us to better understand ecosystem responses to climate change or extreme climate events in different time periods. These results further highlight the importance of extending the knowledge of climatic variables with an ecological perspective. In addition, examining long-term variability in precipitation and temperature indices with ecological relevance provides a reference for rationally setting climate change scenarios in ecosystem models. Current threats to ecosystem functioning and services, together with aggravations of precipitation and temperature extremes, will leave some regions, especially alpine ecosystems, more vulnerable. Thus, linking climatic variables with ecosystem processes more closely is necessary for ecosystem sustainability.

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Appendix A

Appendix A.1. Monthly Precipitation and Temperature of Various Climatic Zones

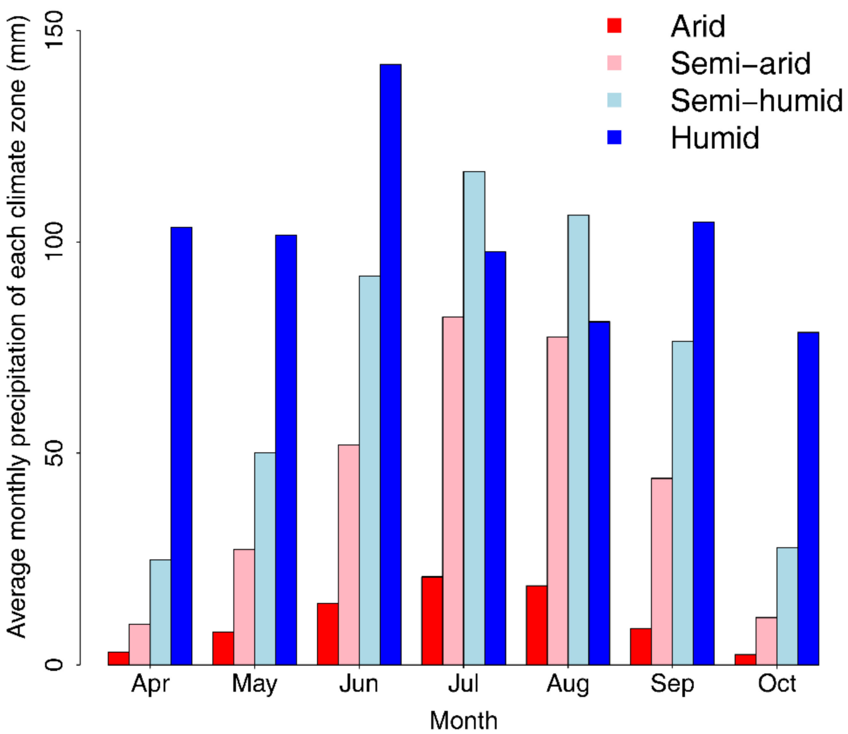

Figure A1. Mean monthly precipitation of each month in (May to September) and around (April and October) the growing season during the year from 1960 to 2015 for climatic zones based on the zoning of precipitation.

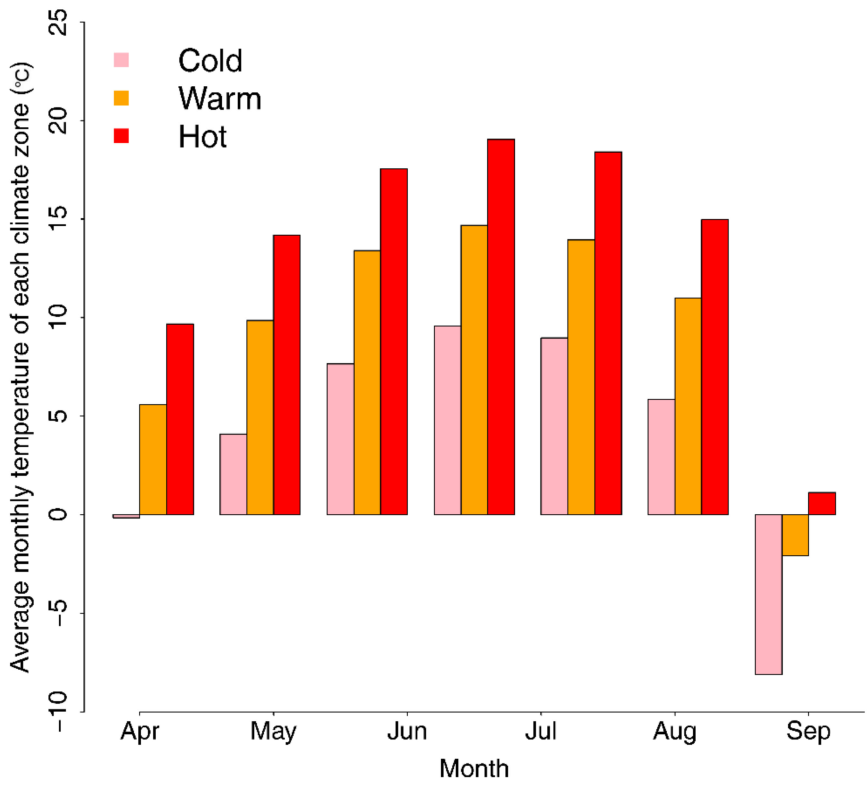

Figure A2. Mean monthly temperature of each month in (May to September) and around (April and October) the growing season during the year from 1960 to 2015 for climatic zones based on the zoning of temperature.

Appendix A.2. The Relationship between Daily Precipitation and Daily Mean Temperature

I analyzed the interactions between daily precipitation and daily temperature. Hydrothermal conditions play a pivotal role in modulating ecosystem functions on the Qinghai-Tibetan Plateau. Neither abundant precipitation with less heat nor high temperatures with little rain is sufficient for vegetation growth. The interactions between daily precipitation and daily temperature were assessed in two aspects: (1) I calculated proportions of daily temperature with specific ranges for all precipitation days. Precipitation days were defined with values greater than 1 mm [7]. Ranges of daily temperature were classified into five categories: < −5 °C, −5–0 °C, 0–5 °C, 5–10 °C, and > 10 °C. (2) I calculated the proportions of daily precipitation with specific ranges for days with temperatures greater than 5 °C. The daily precipitation ranges were classified into three categories: 1–5 mm, 5–10 mm and >10 mm. The assessment of daily precipitation and daily mean temperature was based on data from all weather stations from 1960 to 2015.

For all precipitation days, days with temperatures greater than 5 °C accounted for 72% (Figure A3). Two temperature groups (5–10 °C and >10 °C) occurred at the same level. In contrast, frozen days (< 0 °C) only occupied a proportion of 11% of the total precipitation days. Days with temperatures ranging from 0 to 5 °C accounted for 17%. For all days with temperatures greater than 5 °C (Figure A4), the proportion of days with precipitation values between 1 and 5 mm reached 58%, while strong precipitation days (>10 mm) only had a proportion of 17%. Days with precipitation ranging from 5 to 10 mm accounted for 25%.

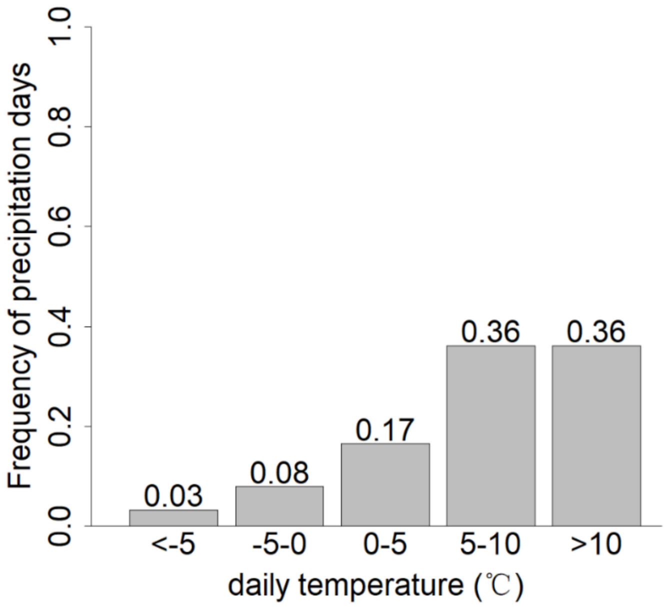

Figure A3. The relationship between daily mean temperature and the distribution of precipitation days.

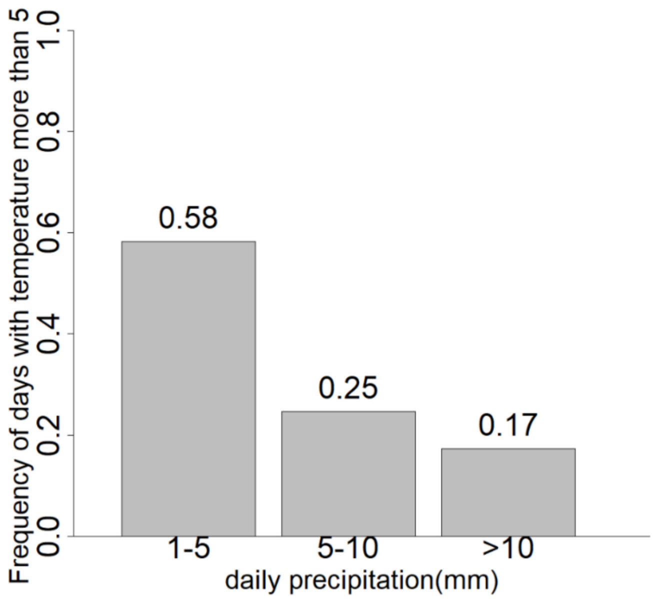

Figure A4. The relationship between daily precipitation and the distribution of days with temperatures greater than 5 °C.

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