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Key Points:

- High-resolution data sets can facilitate the investigation of the complex climate gradient changes in the Qinghai-Tibet Plateau
- The boreal and highland climate types continuously shifted to higher elevation
- The expansion of these two climate types provided more climatic niches for species

Supporting Information:

Supporting Information may be found in the online version of this article.

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Observed Changes of Köppen Climate Zones Based on High-Resolution Data Sets in the Qinghai-Tibet Plateau

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Abstract Emerging and disappearing climate zones are frequently used to diagnose and project climate change. However, little attempt has been made to quantify shifts of climate zones in Qinghai-Tibet Plateau (QTP) based on the high-resolution data sets. Our results show that highland climate was decreased substantially during 1961–2011 and were mainly replaced by boreal climate. We also found that the mean elevation of boreal and highland climate continues to rise, with obvious longitudinal geographical characteristics over the study period. Furthermore, we found that the climate spaces (a climate space defined as the volume of 10°C × 500 mm here) of both boreal and highland climate types tend to be warm and humid ones, which may provide more suitable climate conditions for species to maintain and promote diversity. Characterization of changes in QTP climate types deepens our understanding of regional climate and its biological impacts.

Plain Language Summary Climate classification is the key to simplifying complex climate and helps to deepen the understanding of regional climate change. Based on the high-resolution data set (LZ0025), the sharp climatic gradient features and their potential biological impact on Qinghai-Tibet Plateau (QTP) was quantified. With the temperature increase, the spatial distribution of highland tundra climate was gradually replaced by boreal climate. More importantly, the contraction of highland climate and the expansion of boreal climate has obvious elevation characteristics. In addition, climate spaces of highland and boreal climate types tend to warm and humid ones, which may provide more climatic niches for different species and contribute to regional biodiversity.

1. Introduction

There is growing evidence that the Qinghai-Tibet Plateau (QTP) is experiencing a rapid warming process (Huang et al., 2016). Due to strong feedbacks between glaciers and melting snow, the temperature increase in high mountain areas is faster than in low altitude areas in the past decades (Immerzeel et al., 2020; Isabelle et al., 2020; Quaglia et al., 2020; Zhang et al., 2021). As a result, climate change of QTP has had widespread impacts on regional natural and social systems, such as the increase of extreme events and meteorological disasters (Chen et al., 2017; Defrance et al., 2020; Shugar et al., 2020; Zhao et al., 2019).

Climate classification is a crucial step to understanding the climate itself and its ecological impacts (Beck et al., 2018; Chen & Chen, 2013; Rohli et al., 2015; Rubel & Kottek, 2010). The 21st century is expected to witness unprecedented climate change, and higher altitudes will usually experience greater warming (Berg & McColl, 2021; Gao et al., 2017; McKinnon et al., 2021; Pascolini-Campbell et al., 2021). It is necessary to measure the degree of change in heterogenous climate types in higher altitudes, as it can reflect the unequal spatial pattern of climate change around the world. A widely accepted climate classification system was summarized by Köppen (1936), and several revised versions have been published later (Belda et al., 2014; Feddema, 2005; Holdridge, 1947; Kottek et al., 2006; Peel et al., 2007; Thornthwaite, 1948). In short, based on annual and monthly average temperature and precipitation, Köppen climate classification is used as an alternative to describe natural

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vegetation patterns. The strong overlap between climate and vegetation provides an intuitive link for exploring the ecological impact of climate change.

Currently, the Köppen-Geiger classification is broadly employed to diagnose and project the global and regional climate change from past to future. Based on the historical simulation of the Coupled Model Intercomparison Project Phase 5 (CMIP5), about 5.7% land area is shown to be warmer and drier than the original land climatic conditions from 1950 to 2010 (Chan & Wu, 2015). While, the climate types on about 31.3%–46.3% land areas were projected to shift by the end of 21st century based on the CMIP5 representative concentration pathway (RCP) simulations (Feng et al., 2014). The global temperature increase is considered as the main driving force for changes in global climate zones from the past to future (Burrows et al., 2011). Mahlstein et al. (2013) reported that the pace of global climate types is approximately in line with the global temperature increase under RCP8.5 scenario. However, earlier studies on changes in Köppen climate classes are mainly based on the coarse-resolution simulation data sets or reanalysis data sets (Cui et al., 2021; Diaz & Eischeid, 2007; Gnanadesikan & Stouffer, 2006; Wu et al., 2021; Ying et al., 2012; Yoo & Rohli, 2016; Zhang & Yan, 2014), while research on characterizing the sharp climatic gradients (e.g., in mountainous areas such as QTP) with finer resolution is rare.

Mountain areas provide more opportunities to characterize climatic impacts than lowland, through tracking the microclimates of the complex topography (Cazzolla Gatti et al., 2019; Garcia et al., 2014; Rubel et al., 2017). With the continuous shifting climate zones, the role of mountains as a refuge for biodiversity is likely to be threatened (Rahbek et al., 2019). In the past, many stable and cool climatic patches in mountainous areas provided suitable and different climatic niches for species and improved diversity. However, with the rapid regional warming or drying, when original species cannot adapt to new climatic conditions, the risk of extinction will increase (Peel et al., 2017; Sunday et al., 2012). Thus, it is of great significance to explore the shifting climate zones in mountain ranges and potential biological impacts based on high-resolution data sets (Garcia et al., 2014; Rahbek et al., 2019).

The goal of this research is to measure the extent of the surface area in the QTP covered by each climate type based on the Köppen-Geiger climate classification from 1961 to 2011. Considering that boreal and highland climates account for most of the area in QTP, we focus on characterizing their changes to represent the overall patterns of climate change. We explored (a) spatial changes among major climate types, as well as that in the subtypes of highland climate; (b) the driving force of changes in specific climate types; and (c) the potential biological impacts of changing climate spaces (a climate space defined as the volume of $10^{\circ}\text{C} \times 500 \text{ mm}$ here) on species. Our results can help us to understand the climate of QTP and the biological impact of its continuous change.

2. Data and Methods

2.1. Observed Meteorological Data Sets

The observational air temperature and precipitation gridded data sets (LZU0025) are provided by the Data Publisher for Earth & Environmental Science (PANGAEA), including five periods, that is, 1961–1970 (T1), 1971–1980 (T2), 1981–1990 (T3), 1991–2000 (T4), and 2001–2011 (T5). The monthly temperature was retrieved from 1,153 meteorological stations in China and surrounding countries. The precipitation data were obtained from 1,202 meteorological stations in China and surrounding countries. The data set was reconstructed by the thin plate smoothing method embedded in ANUSPLIN software. In particular, through the assessment of diagnostic statistics, error statistics, and comparison with other data sets, these gridded climatic data sets were proved accurate and can be used to describe the climatic characteristics of complex terrain in China (Zhao et al., 2019). In view of the very high resolution (0.025°) and long time series of this data set, we used it to evaluate the temporal and spatial characteristics of QTP Köppen climate types in this study.

2.2. Köppen-Geiger Climate Classification

We used the Köppen-Geiger climate scheme (Peel et al., 2007) to categorize the climate of the QTP into tropical (A), arid (B), temperate (C), boreal (D), and highland (E) climate types. Moreover, two typical subtypes present

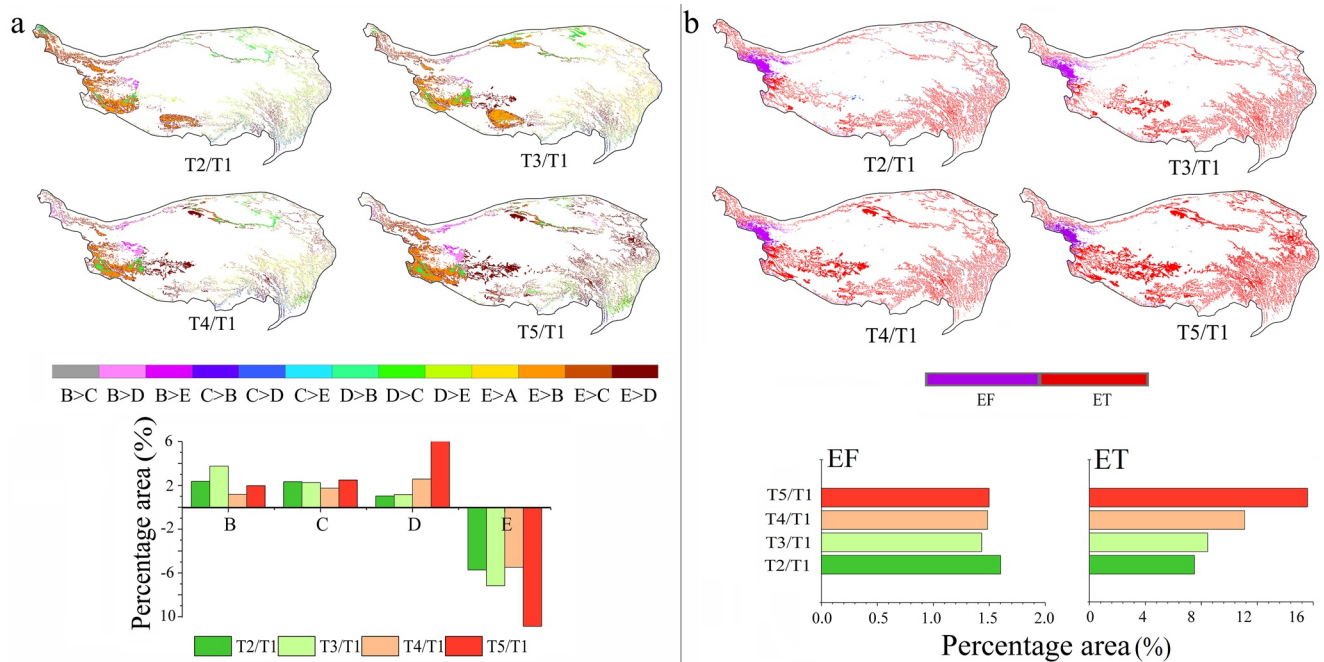


Figure 1. (a) The spatial shifts of major Köppen climate zones and (b) Disappearing frost (EF) and tundra (ET) climates in QTP for 1971–1980 (T2), 1981–1990 (T3), 1991–2000 (T4), and 2001–2010 (T5) relative to 1961–1970 (T1). B–E represents arid, temperate, boreal, and highland climate types, respectively.

at the QTP were studied in detail, namely highland frost (EF) and highland tundra (ET) climates (Table S1). Because Köppen types also include seasonality of the precipitation (and temperature, for that matter), we did not explore changes in the finer Köppen climatic types (e.g., DFB, DWB, etc.). The climatic type was calculated from mean monthly temperature and precipitation at each grid point. The percentage of each climate type was estimated by the number of specific grid boxes. Note that a method of a 5-year running average was used to eliminate possible short-term changes of natural variability, as year-to-year changes include greater internal changes that may not be related to climate trends (Mahlstein et al., 2013).

2.3. Sensitivity Analysis

To assess the sensitivity of temperature and precipitation of QTP climate zones, we designed two different climatic scenarios for Köppen-Geiger climate schemes. In the first climatic scenario that is mainly triggered by temperature (S_T), precipitation is set to be the monthly data of 1961, while the time series from 1961 to 2011 is used for temperature. In the second climatic scenario that is mainly triggered by precipitation (S_P), temperature is set to be the monthly value of 1961 while the precipitation varies with time from 1961 to 2011. Compared to the actual change in the reference scenario (S_0), we can distinguish the main driving force in the specific climate type.

3. Results

3.1. Spatial Changes of Shifting Climate Types

Figure 1 shows the spatial and temporal characteristics of major climate types relative to T1 (1961–1970) in QTP from 1961 to 2011. The most apparent spatial feature is that the disappearing highland (E) climate zone is mainly replaced by the boreal (D) climate zone. Spatially, the shifts compared to T1 were detected in the surrounding areas of the QTP, especially in the Himalayan (Southwest) and Hengduan (Southeast) Mountains.

A clear spatial shift in the marginal mountainous area of Qaidam Basin in the north of the QTP was also observed. Temporally, compared to T1, the percentage of area change of arid (B) and temperate (C) climate types fluctuated less during the study period. However, the percentage of area change of boreal climate expanded apparently from 1.03% (T2/T1) to 6.42% (T5/T1), while the highland climate area shifted from -5.72% (T2/T1) to -10.87% (T5/T1).

In terms of highland (E) climate, Figure 1b shows that the percentage of area change of tundra (ET) climate is much lower than that of frost (EF) climate over the study period. Based on the Köppen-Geiger climate scheme, in the context of regional warming, this signal should be attributed to the ability of ET shifting to a wide variety of D subtypes or EF. However, the other direction (EF changed to D climate type) cannot occur. Furthermore, the effects of the increased humidification likely lead to increased riming in EF climates, with partially offsetting the warming in ice-albedo feedback. Therefore, the regions remain cold enough to prevent EF from changing in area as much as the ET climates. Compared to T1, the percentage of area of EF changed slightly over the four periods while ET decreased pronouncedly from 8.07% (T2/T1) to 16.76% (T5/T1). The disappearing regions of ET are mostly distributed along the mountain range, with obvious longitudinal characteristics.

3.2. Geographic Characteristics of Highland and Boreal Climate Types

Figures 2a and 2b show that the area of boreal and highland climates has an apparent response to elevation from T1 to T5. In general, the spatial distribution of boreal climate zone expands with the increase of elevation. A negative relationship was observed for the area of highland climate varying with elevation increase. Specifically, the percentage area of boreal climate has rapidly increased from 13.38% to 19.84%, while the corresponding elevation has also increased from 3,675 to 3,921 m. Meantime, the percentage area of highland climate has clearly decreased from 69.87% to 58.92%, with the mean elevation increasing from 4,749 to 4,802 m.

The disappearance of highland climate zones in huge mountain areas is replaced by other climate zones in elevation, especially by the boreal climate zone. Furthermore, we detected a clear longitudinal feature between boreal (Figure 2c) and highland (Figure 2d) climate types, which was well fit by quadratic model between elevation and longitude ($p < 0.01$, t -test). The longitudinal mean elevation is gradually increased between T1 and T5 (excluding T2). This is probably due to the distribution of huge East-West (e.g., Nianqing Tanglha mountains) and North-South mountains (e.g., Hengduan mountains) on the plateau, resulting in the shifts of boreal and highland climates to the higher elevation.

3.3. Drivers of Shifting Climate Zones

Table 1 shows the average ratios of percentage area of S_p and S_T to that of S_0 in the specific climate type in QTP over the five periods. Overall, when the temperature is held constant (S_p), the area of arid climate is approximately the same as observed changes (ratio = 0.98/1.0). On the contrary, when the precipitation is held constant (S_T), areas of boreal climate (ratio = 0.95/1.0) and highland climates (ratio = 0.99/1.0) are closer to the observed changes. In the temperate type, both temperature and precipitation affect its evolution because of the ratios between S_T/S_0 (ratio = 0.74/1.0) and S_p/S_0 (ratio = 0.67/1.0) are very close. Since boreal and highland climate types occupied most of the plateau, these sensitivity results clearly demonstrate that temperature plays a larger role in the evolution of overall major climate zones than precipitation.

Based on the probability distribution curves in Figure 3, the decadal change of main driving force tends to be humid and warm. For example, the overall heavier precipitation was observed from T1 to T5 for the arid climate (Figure 3a). Regarding the climate types of boreal and highland, which were mainly influenced by temperature, an increasing temperature was observed from T1 to T5. An exception is the temperate climate. Because the temperate climate zone is mainly distributed in the low elevation regions of QTP, the local temperature increase is unlikely to cause the significant spatial expansion due to the barrier effect of Tibetan Plateau (Chen et al., 2014; Kitoh, 1997).

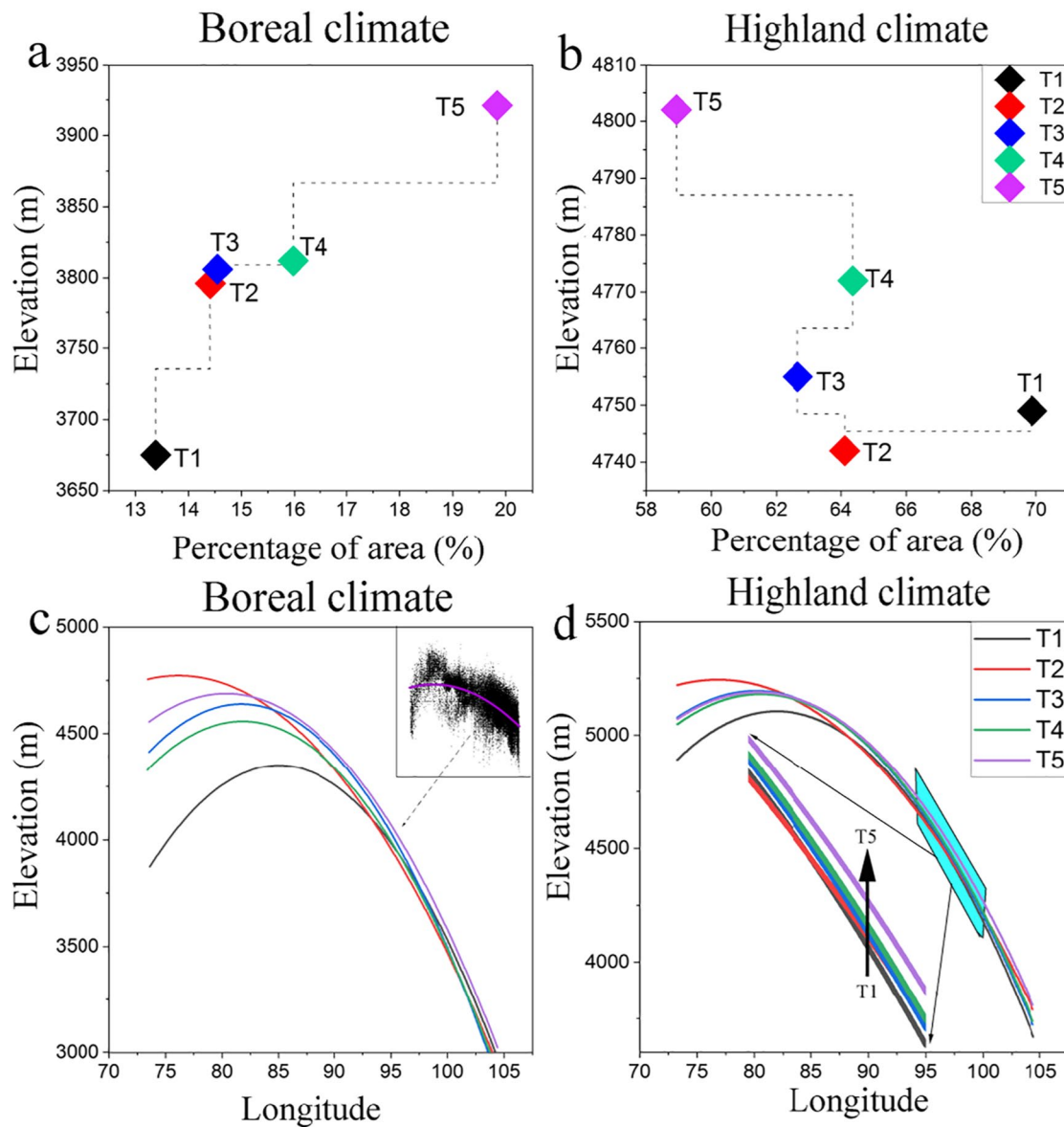


Figure 2. Relationship between the mean elevation and percentage areas of (a) Boreal and (b) Highland climates in different time periods. Quadratic fits between longitude and elevation in different colors (c) Boreal and (d) Highland climates.

3.4. Potential Impacts of Shifting Climate Zones on Biomes

Climate spaces are crucial to generate and maintain local species diversity (Rahbek et al., 2019). Figure 4 shows that the climatic units (black points) which composed of temperature and precipitation expands pronouncedly between T1 and T5. Further, the number of climate spaces (cyan boxes) occupied by climate units also shows an expanding trend. For boreal climate, the number of climate spaces expands from 14 (Figure 4a) to 17 (Figure 4b). Meantime, for highland climate, the number of climate spaces increases from 14 (Figure 4c) to 18 (Figure 4d). Both boreal and highland climates are mainly focusing on warming and humidification. Considering the complex topography of QTP, the expansion of climate spaces is likely to promote the ability of many species with slightly different climatic niches to coexist in a specific spatial range. However, it should be noted that climate warming will

Table 1
Ratios of Specific Climate Types of S_p/S_0 and S_T/S_0 During T1–T5

Types	Arid		Temperate		Boreal		Highland	
	S_p/S_0	S_T/S_0	S_p/S_0	S_T/S_0	S_p/S_0	S_T/S_0	S_p/S_0	S_T/S_0
Mean								
Ratios	1.26	0.98	0.67	0.74	0.95	0.77	0.99	1.12

Note. Bold represents the main climate factor of a specific climate type.

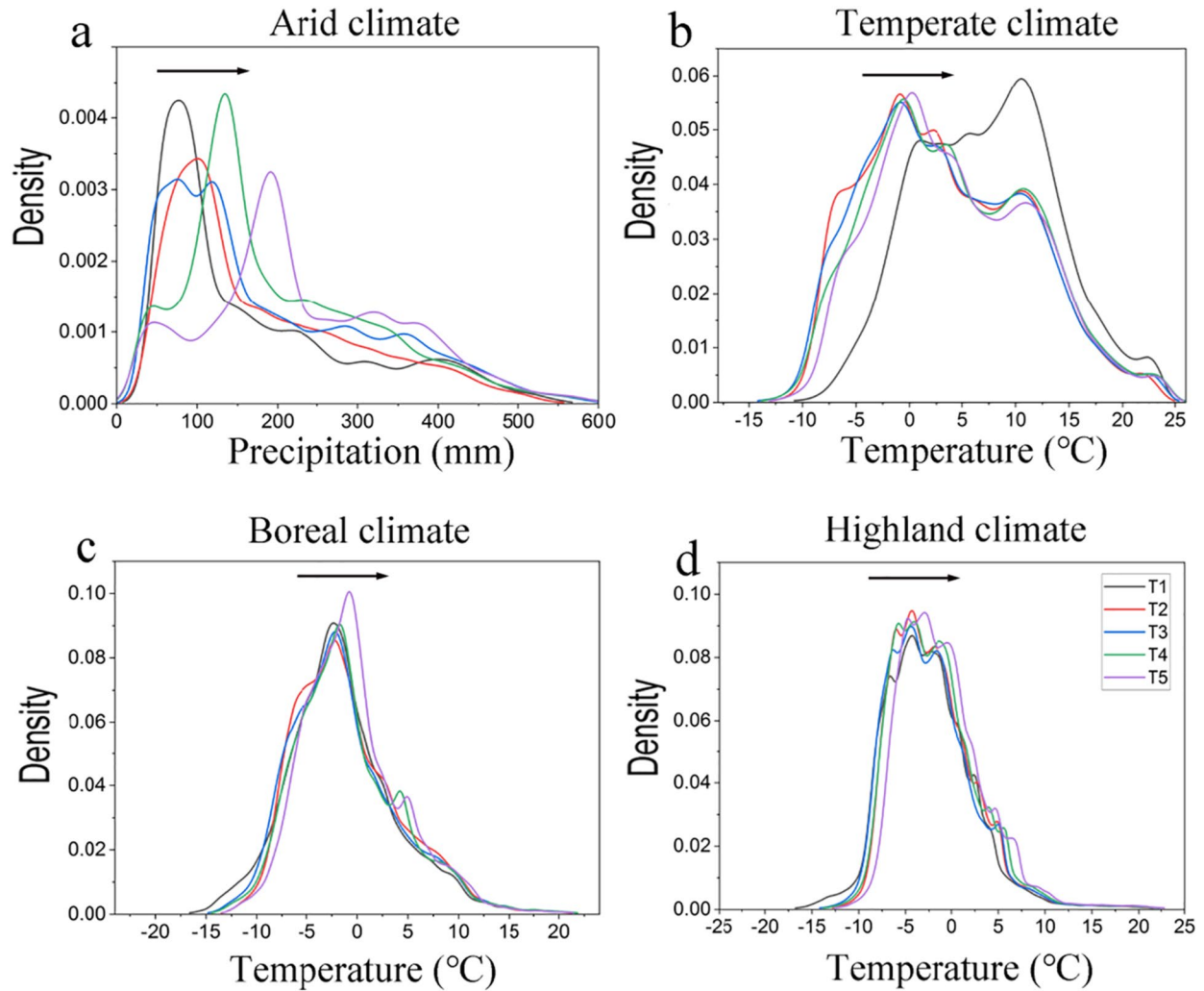


Figure 3. Probability density functions of the main driving force in (a) Arid, (b) Temperate, (c) Boreal, and (d) Highland climate types from T1 to T5. Black arrows represent the direction of the curve transition from T1 to T5.

also change the original cool conditions in mountainous areas. When native species cannot adapt to new climatic conditions, they are expected to increase the risk of extinction.

4. Conclusions

The availability of high-resolution data sets allowed re-evaluation of the distribution of the Köppen-Geiger climate types on the elevation scale. Considerable temperature rise has caused rapid shifts between major climate types in the QTP since the 1960s. The area expansion of boreal climate is accompanied by the rise of mean elevation from 3,675 to 3,921 m; on the contrary, the shrinking of highland climate toward higher elevation has caused change from 4,749 to 4,802 m. Obvious longitudinal geographical characteristics were also observed in this period. Sensitivity-based results indicate that the temperature has driven the evolution of overall climate zones to warmer types in the QTP. The expansion of climate spaces of boreal and highland climates tends to be more warming and humid ones, providing a more remarkable volume of suitable habitats and more potentials for the species' redistributions. The research on shifting climate types of the QTP will deepen the understanding of the potential redistribution mechanism of life on the altitude gradient.

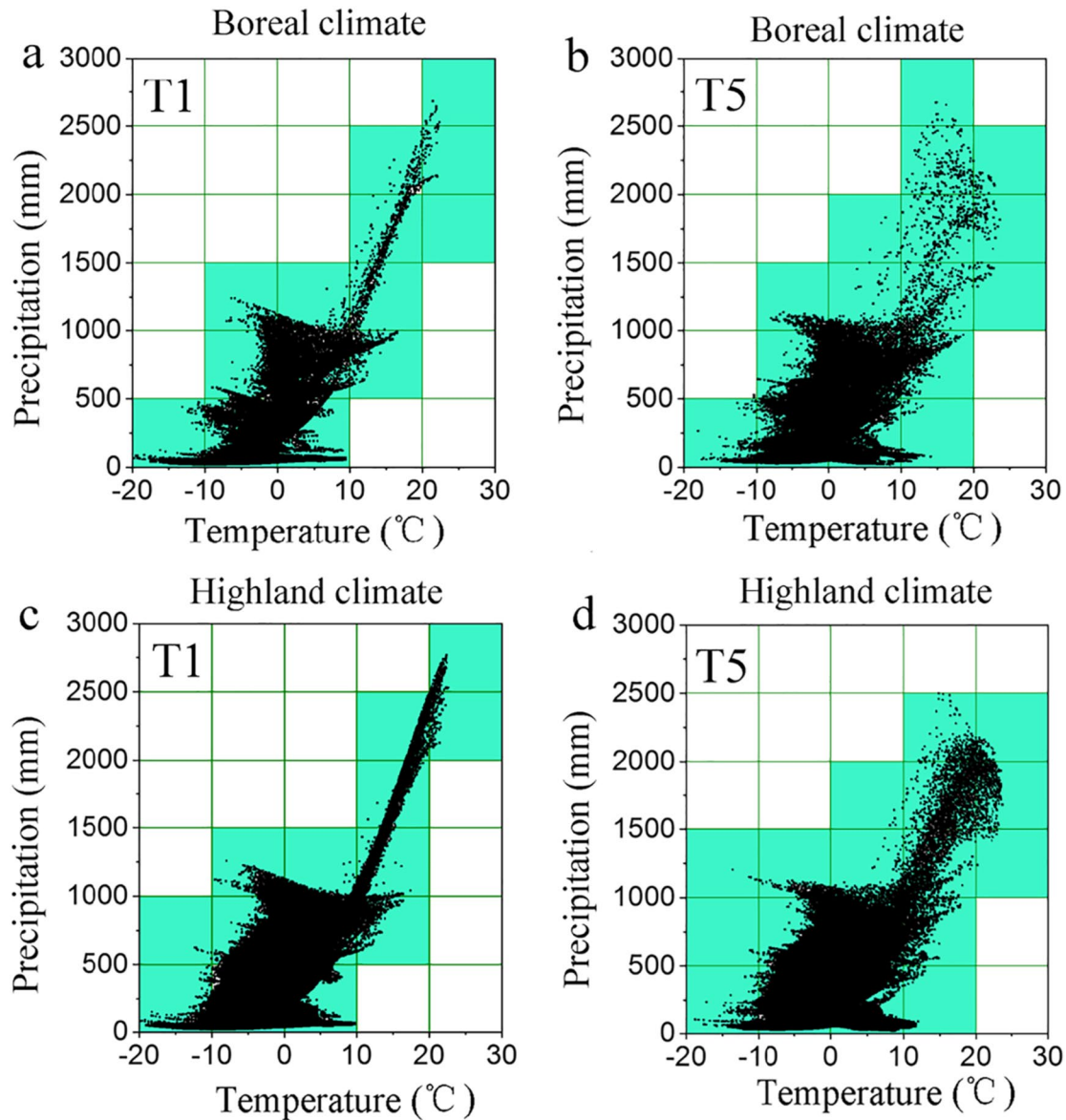


Figure 4. The climate spaces of (a and b) Boreal and (c and d) Highland climate types between T1 and T5. Each box represents a climate space ($10^{\circ}\text{C} \times 500\text{ mm}$). Cyan box refers to the climate space involved in the climate volume which composed by temperature and precipitation.

Data Availability Statement

The raw data used in this study were published open access by Zhao et al. (2019) and are available on PANGAEA via <https://doi.pangaea.de/10.1594/PANGAEA.895742>. In this study, our data are freely available at the Mendeley via DOI <https://doi.org/10.17632/623rm9xswy.1>.

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