Spatial and temporal variability of key bio-temperature indicators on the Qinghai–Tibetan Plateau for the period 1961–2013

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ABSTRACT: The ecosystems of the Qinghai–Tibetan Plateau (QTP) are highly sensitive to climate change, the effects of which can be expressed through alterations to some key thresholds, including bio-temperature. However, to date, few studies have investigated variations in bio-temperature on the QTP in the context of climate change. To address this, the present study selected the following key indicators of bio-temperature: mean temperature of the warmest month (TWM); mean temperature of the coldest month (TCM); accumulated temperature above 10 °C (AT₁₀), 5 °C (AT₅), and 0 °C (AT₀); and number of days with daily mean temperature above 10 °C (DT₁₀), 5 °C (DT₅), and 0 °C (DT₀). These indicators were selected owing to their roles in the growth and distribution of vegetation on the QTP. The trends exhibited by these indicators were examined on basis of the data obtained from 71 observation stations on the QTP from 1961 to 2013. The results demonstrate that both TWM and TCM at the regional scale exhibited significant rising trends over this period, although TCM increased at a considerably faster rate. Spatially, the greatest increases in TWM and TCM were observed in the Qaidam basin desert and Guoluo–Naqu alpine shrub meadow regions. Additionally, AT₁₀, AT₅, and AT₀ exhibited increasing trends, with AT₀ increasing most rapidly and exhibiting the most significant changes, followed by AT₅ and then AT₁₀. Similarly, DT₀ exhibited a greater overall increase than DT₁₀ and DT₅. Spatially, AT and DT exhibited asymmetrical change, i.e. large increases in AT did not correspond to large increases in DT. In general, all the bio-temperature indicators considered indicate pronounced rising trends over this recent five decades. This was likely due to rising air temperatures across the QTP, which have affected the structures and functions of alpine ecosystems.

KEY WORDS climate change; Qinghai–Tibetan Plateau; bio-temperature; trends

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1. Introduction

Climate change characterized by rising air temperature can be considered almost entirely irreversible; consequently, it has attracted considerable attention from the general public, researchers, and government officials. Observations have indicated that the global mean surface has warmed by approximately 0.85 °C over the past 100 years, with temperature projected to increase by a further 0.4–4.8 °C by 2100 (IPCC, 2013). Such warming of the climate can induce substantial variations in the composition, structure, and function of terrestrial ecosystems, thus influencing the role of terrestrial ecosystems as carbon sinks. Additionally, warming climate may favour the introduction of new species in areas previously limited by unfavourable thermal conditions.

The Qinghai–Tibetan Plateau (QTP), which has an average altitude higher than 4000 m a.s.l., is commonly referred to as the ‘third pole’ of the Earth (Qiu, 2008). The

QTP is characterized by its vast area and strong thermal and dynamic forcing, which combine to make it a unique climatic unit distinct from other regions at the same latitude. Moreover, the region exerts a strong influence on both atmospheric conditions in its surrounding, as well as regional and global climatic conditions; therefore, the QTP is considered to be the driver and amplifier of global climate change (Feng *et al.*, 1998). Several previous studies have discussed climate change within the QTP, focusing primarily on increases in surface air temperature. The results of these studies suggest that temperature rises substantially in winter and spring (Xu *et al.*, 2008) and that the average temperature since the 1990s is considerably higher than that before this time (Wei *et al.*, 2003; Wang *et al.*, 2004). Moreover, it has been shown that the warming trend is stronger in the northeast and southwest parts of the plateau than in the southeast (Wu *et al.*, 2005), and the orientations of major ridges exert a clear effect on the spatial distribution of temperature variations across the plateau (Du, 2001; Li *et al.*, 2003). However, it should be noted that previous studies have typically focused on analysis of the factors governing climate change in the region, rather than on the consequent ecological effects.

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Alpine ecosystems are particularly vulnerable to climate change on the QTP, and even slight changes in the climate can induce large changes in such ecosystems (Zhang *et al.*, 1996). Climate change primarily affects vegetation by altering some key thresholds, including bio-temperature thresholds. In particular, climate change can be expressed through changes in the following variables: mean temperature of the warmest month (TWM); mean temperature of the coldest month (TCM); accumulated temperature above 10 °C (AT₁₀), 5 °C (AT₅), and 0 °C (AT₀); and number of days with daily mean temperature above 10 °C (DT₁₀), 5 °C (DT₅), and 0 °C (DT₀). These bio-temperature indicators are associated closely with plant growth and distribution; therefore, they are often adopted as thresholds in models designed to predict the future effects of climate change on ecosystems (Kaplan *et al.*, 2003; Sitch *et al.*, 2003). Numerous models have been developed on the basis of bio-temperature indicators to predict plant phenology and crop production; such models have typically been demonstrated to be robust (Grigorieva *et al.*, 2010; Fu *et al.*, 2012; Richardson *et al.*, 2012). Thus, changes in key bio-temperature metrics can be considered to indicate changes in the structure, function, and distribution of vegetation. Nevertheless, studies investigating bio-temperature on the QTP have been rare in recent decades and have focused primarily on the thermal growing season. For example, Liu *et al.* (2006) analysed variation in the length of the thermal growing season over the eastern and central QTP during 1961–2003 on the basis of meteorological data, whereas Dong *et al.* (2012) examined variations at the start, end, and across the length of the growing season throughout the QTP during 1960–2009.

In the present study, TWM, TCM, AT₁₀, DT₁₀, AT₅, DT₅, AT₀, and DT₀ were selected as key indicators of bio-temperature; all these variables have well-defined ecological definitions and have been applied widely in previous studies. Based on these indicators, we investigated temporal and spatial trends in bio-temperature on the QTP from 1961 to 2013. Our results will enhance future ecological studies and support decision-making regarding ecological construction on the plateau.

2. Methods and data

2.1. Bio-temperature indicators

On the plateau, TWM determines the normal growth of vegetation, whereas the lowest temperature in the warmest month represents the minimum temperature requirement of alpine vegetation during the growing season. The latter parameter is also a general indicator of the efficiency of solar energy [Larcher, 1980; Integrated Scientific Expedition to Tibetan Plateau, Chinese Academy of Sciences (ISEQXP CAS), 1985], and TWM is often applied to evaluate whether the consumption of energy during respiration exceeds energy production or whether such metabolic processes cease to operate. However, on the QTP, the maximum value of TWM remains relatively low, which does not obviously inhibit vegetation growth

there. TCM acts to delineate the boundaries of vegetation distribution and can be used to indicate the sustainability of vegetation within these boundaries, particularly at low temperatures. For plants less able to adapt to environmental conditions, low temperatures may result in freezing damage or death. In this context, TCM represents the lowest average temperature that the vegetation present can tolerate (Prentice *et al.*, 1992). On the QTP, alpine vegetation such as alpine meadow, alpine steppe, and alpine desert can survive at low TCM values owing to their adaptation to the low-temperature environment (ISEQXP CAS, 1988). Conversely, the maximum value of TCM has often been selected to represent a threshold for chilling for seasonal vegetation (Box, 1981).

Vegetation requires both a particular temperature to initiate growth and a total amount of temperature to sustain the complete life cycle. The total amount of temperature is known as the accumulated temperature or the growing degree-days (Richardson *et al.*, 2012; Fernández-Long *et al.*, 2013) and typically represents a plant's growing-season heat requirements. Owing to the differences in threshold temperatures among various vegetation types, the accumulated temperature must be quantified from variable starting points (ISEQXP CAS, 1988; Zheng *et al.*, 2010; Fernández-Long *et al.*, 2013). During the growing season on the QTP, where the daily mean temperature is above 0 °C, snow and ice melt and frozen soil thaws. Meanwhile, the alpine meadow begins to bud-burst and crops suited to cool conditions, such as highland barley, can be sowed. When the daily mean temperature exceeds 5 °C, the alpine meadow turns green, and vegetables, such as rape and potato, can be planted. Subsequently, when daily mean temperature exceeds 10 °C, the leaves of most arbor species sprout or wither; moreover, most thermophilic crops begin to grow at around 10 °C (Qiu and Lu, 1980; ISEQXP CAS, 1985). Thus, the accumulated temperature over 10 °C is an important and universal index used in the evaluation of climatic heat resources in China. Nevertheless, it is reasonable to describe heat characteristics with reference to both the duration of elevated temperatures and the value of accumulated temperature, particularly because the accumulated temperature is determined by both the duration of elevated temperature and the daily mean temperature (Zheng, 1996; Wu *et al.*, 2002), especially in regions with lower annual mean temperature. For instance, the value of accumulated temperature above 10 °C is small owing to the low summer temperatures on the QTP, despite the relatively prolonged duration of these temperatures.

2.2. Data

In the present study, observed daily records of mean temperatures from 71 meteorological stations during the period 1961–2013 were provided by the China Meteorological Administration. The data underwent carefully quality check and homogeneity adjustment to achieve high quality (China Meteorological Administration, 2003; Wang, 2004). Observation stations were removed from the

data set if: the station was built after 1961, the station was removed before 2013, or more than 5% of the data from the station was missing. We detected total 228 missing daily records in the dataset, which belong to 31 meteorological stations. The missing daily records mostly occurred in 1968, 1969, and 1970, summing to 187 records. The most missing data were detected in the Jiangzi station, approximately to 43 missing records, which mainly distributes in spring and summer. To ensure the completeness and continuity of the data, a few missing values were interpolated through linear regression from adjacent stations with complete time series during the same period. TWM, TCM, AT_{10} , DT_{10} , AT_5 , DT_5 , AT_0 , and DT_0 were calculated based on these daily observation data.

2.3. Methods

After considering the monthly mean temperatures observed in a given year, the highest monthly mean temperature was selected to represent TWM and the lowest to represent TCM. Then, AT_{BT} was defined as an integration of the daily mean temperature above a temperature threshold or base temperature, whereas DT_{BT} was defined as the number of days with daily mean air temperature above a temperature threshold or base temperature. These were calculated as follows:

$$AT_{BT} = \sum_1^n (T_{\text{mean}} - T_{BT}) \text{ if } T_{\text{mean}} > T_{BT}, \quad (1)$$

$$DT_{BT} = \sum_1^n (1) \text{ if } T_{\text{mean}} > T_{BT} \quad (2)$$

where n is the number of days in a given year, and T_{mean} and T_{BT} are the daily mean temperature and the temperature threshold, respectively. In this study, we selected 0, 5, and 10 °C as the temperature thresholds associated with climate change for the ecosystems on the QTP. To reduce the effects of extreme values, T_{mean} was defined as five consecutive mean values for daily mean temperature.

The slopes of the linear regressions, calculated by the least-squares method, were used to examine temporal trends in bio-temperature, with positive and negative values indicating increases and decreases, respectively. The Mann–Kendall method, which has been used widely to investigate changes in meteorological and environmental data, was adopted to assess the reliability of the observed trend (Liu *et al.*, 2008; Liang *et al.*, 2010). This non-parametric test is more applicable than typical parametric methods for abridged data or data sets with non-normal distributions, because it requires no standard pattern for the distribution of samples and is not affected by sporadic outliers (Sneyers, 1990).

The climatic conditions of the QTP are complex: the climate varies from subtropical in the south to sub-cold in the north and from humid in the southeast to dry in the northwest. The ecosystems of the QTP are diverse, with forests in the eastern region, alpine grasslands in the central region, and deserts in the northwestern region. The macro-distribution of these ecosystems forms several

eco-regions with unique characteristics. Based on the ecological regionalization scheme of Zheng (2008), the QTP has been divided into 11 eco-regions based on similarities in terrain, climate, and vegetation type (Figure 2), as follows: Plateau sub-cold sub-humid, Guoluo–Naqu Plateau mountain alpine shrub–meadow region (HIB1); Plateau sub-cold semi-arid, Southern Qinghai Plateau, and wide valley alpine meadow–steppe region (HIC1); Plateau sub-cold semi-arid, Qiangtang Plateau lake basin alpine steppe region (HIC2); Plateau sub-cold arid, Kunlun high mountain, and plateau alpine steppe region (HID1); Plateau temperate humid/sub-humid, western Sichuan and eastern Xizang high mountain, and deep valley coniferous forest region (HIIA/B1); Plateau temperate semi-arid, Qilian mountains of the eastern Qinghai high mountain, and basin coniferous forest and steppe region (HIIIC1); Plateau temperate semi-arid, southern Xizang high mountain, and valley shrub–steppe region (HIIIC2); Plateau temperate arid, Qaidam Basin desert region (HIIID1); Plateau temperate arid, North Kunlun mountain desert region (HIIID2); Plateau temperate arid, Ngali mountain desert region (HIIID2); and Plateau subtropical humid, southern East Himalayas seasonal rainforest, and evergreen broad-leaved forest region (HIIIA1). These eco-regions were utilized as a framework for analysis of spatiotemporal variations in bio-temperature.

3. Results

3.1. Changes in TWM and TCM

At the regional scale, TWM on the Tibetan Plateau has increased by 0.031 °C year^{−1} over the last 50 years (Figure 1(a)), with a confidence interval of 0.011 °C year^{−1} and a variation range of 0.002–0.090 °C year^{−1}. All observation stations experienced increasing TWM (Figure 2(a)), although the rate of this increase varied significantly between different eco-regions. For example, TWM in the HIIID1, HIC1, and HIB1 regions exhibited a pronounced rising trend, with an increase of over 0.030 °C year^{−1}; the largest increase (0.090 °C year^{−1}) was observed at the Mangya station in the HIIID1 region, where average TWM over the past 50 years has been approximately 15.600 °C. A TWM increase of less than 0.031 °C year^{−1} was concentrated primarily in the HIC2 and HIIA/B1 regions, with the smallest increase (0.002 °C year^{−1}) observed at the Henan station, although this trend did not pass the significance test. Of the 71 stations considered in the present study, 58 were significant at the 0.01 level, accounting for 81% of all stations.

TCM at the regional scale has increased by 0.046 °C year^{−1} (Figure 1(b)), with a confidence interval of 0.014 °C year^{−1} and a variation range of −0.068 to 0.152 °C year^{−1}. The rates of change of TCM exhibited a positive trend for most of the Tibetan Plateau (Figure 2(b)), with the exception of the Henan and Tashikuer stations. Similar to TWM, greater increases in TCM were found primarily for the HIIID1 and HIB1 regions, which experienced increases of 0.05–0.10 °C year^{−1}. The largest

Figure 1. Inter-annual variations in mean temperature of the (a) warmest and (b) coldest months at regional scale on the Qinghai–Tibetan Plateau during the period 1961–2013. In the figures, straight lines refer to linear trends.

Figure 2. Trends in mean temperature of the (a) warmest and (b) coldest months on the Qinghai–Tibetan Plateau during the period 1961–2013.

significant increment, $0.050^{\circ}\text{C year}^{-1}$, was found for the Bange station, whose mean TCM and TWM during the period 1961–2013 were -12.095 and 9.120°C , respectively. For TCM, 67 (61) stations were found to be significant at the 0.05 (0.01) level, representing 94% (85%) of the total. Compared with the TWM trend, TCM exhibited a greater increase on the plateau; moreover, the results of the significance level test indicate that TCM exhibited a more pronounced increasing trend than TWM.

3.2. Changes in AT and DT

On the Tibetan Plateau, the average AT_{10} at the regional scale exhibited an increase at a rate of $2.451^{\circ}\text{C year}^{-1}$ (Figure 3(a)), with a confidence interval of $0.618^{\circ}\text{C year}^{-1}$ and a variation range of 0.000 – $10.366^{\circ}\text{C year}^{-1}$. The magnitude of the increase in AT_{10} increased gradually from the central plateau to the southwest and northwest (Figure 4(a)). Moreover, greater increases in AT_{10} ($>3^{\circ}\text{C year}^{-1}$) were concentrated primarily in the HIID1 and HIIC2 regions. The stations in the HIC1 and HIC2 regions recorded only slight increases

(less than $1^{\circ}\text{C year}^{-1}$), and only a few stations in the east recorded a decline in AT_{10} . According to the Mann–Kendall method, 64 stations passed the 0.01 significance test, representing 90% of all stations considered here. DT_{10} also increased at the regional scale, at a rate of 0.366 days year^{-1} (Figure 3(b)), with a confidence interval of 0.100 days year^{-1} and a variation range of -0.028 to 1.235 days year^{-1} . The greatest increases in DT_{10} were found for the HIID1, HIIC1, and HIIC2 regions and the western part of HIB1, with rates exceeding 0.3 days year^{-1} (Figure 4(b)). Of the 71 stations considered, 69 exhibited a positive trend and 60 of these stations passed the 0.01 significance test. These results correspond broadly to those obtained for AT_{10} .

The regional average AT_5 exhibited a significant increase at the rate of $4.212^{\circ}\text{C year}^{-1}$ during the last 50 years (Figure 5(a)), with a confidence interval of $1.070^{\circ}\text{C year}^{-1}$ and a variation range of -0.167 to $15.020^{\circ}\text{C year}^{-1}$. Moreover, this variable exhibited greater increases ($>5^{\circ}\text{C year}^{-1}$) in the HIID1 and HIIC2 regions, while smaller increases ($<3^{\circ}\text{C year}^{-1}$) in the HIC1 and

Figure 3. Inter-annual variations in (a) accumulated temperature above 10 °C and (b) number of days with daily mean temperature above 10 °C at regional scale on the Qinghai–Tibetan Plateau during the period 1961–2013. In the figures, straight lines refer to linear trends.

Figure 4. Trends in (a) accumulated temperature above 10 °C and (b) number of days with daily mean temperature above 10 °C on the Qinghai–Tibetan Plateau during the period 1961–2013. In the figures, white circles indicate no value because daily mean temperature is below 10 °C in these observation stations.

HIB1 regions, and the eastern part of the HIIA/B1 region (Figure 6(a)). According to the Mann–Kendall method, 5 of the stations considered were significant at the 0.05 level and 63 at the 0.01 level; these 63 stations constitute 88% of all stations considered. DT_5 at the regional scale increased at a rate of 0.321 days year^{−1} (Figure 5(b)), with a confidence interval of 0.094 days year^{−1} and a variation range of −0.228 to 0.862 days year^{−1}, and the larger increases in this indicator were concentrated primarily in the HIIC2 region (Figure 6(b)). DT_5 and AT_5 were found to exhibit almost the same trends, except for several differences captured at the Xining and Jiali stations, where a decline in DT_5 was accompanied by an increase in AT_5 . However, this trend did not pass the significance test. For AT_5 , 12 stations were found to be significant at the 0.05 level and 53 stations at the 0.01 level; these 53 stations constitute 74% of all stations considered. In brief, the results show that DT_5 changed less significantly than AT_5 .

Average AT_0 at the regional scale exhibited a pronounced increase at a rate of 5.922 °C year^{−1} (Figure 7(a)),

with a confidence interval of 1.425 °C year^{−1} and a variation range of −1.364 to 18.426 °C year^{−1}. Over the past 50 years, larger increases in AT_0 (>10 °C year^{−1}) occurred in the HIIC2, HIID1, and HIIC1 regions, and in the south of the HIIA/B1 region (Figure 8(a)). Only slight increases in AT_0 were found for the HIC1 and HIC2 regions, which are located at higher altitudes and experience lower annual average temperatures than the other stations. Of the 71 stations considered, 67 were found to be significant at the 0.01 level, accounting for 94% of all stations considered. DT_0 also increased overall, at a rate of 0.373 days year^{−1} (Figure 7(b)), with a confidence interval of 0.092 days year^{−1} and a variation range of −0.181 to 1.218 days year^{−1}. The most rapid increases in DT_0 occurred in the HIIC2 and HIID1 regions and in the south-east of the HIIA/B1 region, while slower increases in the HIC1 and HIIC2 regions (Figure 8(b)). A negative trend was recorded at the Henan station (Figure 5(b)), although this trend did not pass the significance test. However, for DT_0 , 64 (3) stations were found to be significant at the 0.01

Figure 5. Inter-annual variations in (a) accumulated temperature above 5 °C and (b) number of days with daily mean temperature above 5 °C at regional scale on the Qinghai–Tibetan Plateau during the period 1961–2013. In the figures, straight lines refer to linear trends.

Figure 6. Trends in (a) accumulated temperature above 5 °C and (b) number of days with daily mean temperature above 5 °C on the Qinghai–Tibetan Plateau during the period 1961–2013.

(0.05) level, constituting 90% (4%) of all stations. However, the changes in DT_0 were found to be less significant than those in AT_0 .

4. Discussion

In the present study, we analysed trends in key bio-temperature indicators (including TWM, TCM, AT_{10} , DT_{10} , AT_5 , DT_5 , AT_0 , and DT_0) for the QTP for the period 1961–2013. Analysis of TWM and TCM showed that most stations on the QTP recorded an increasing trend, although some asymmetries were observed between the TWM and TCM trends. Broadly, the relationship between the TWM and TCM trends can be separated into three distinct categories: (1) TWM increases markedly in tandem with TCM but with a smaller magnitude, as recorded by 57% of the stations; (2) TWM increases markedly in tandem with TCM but with a larger magnitude, as exemplified by the Linzhi station in the southeast of the HIIA/B1 region; and (3) TWM increases markedly but TCM decreases significantly, as observed at the Henan

station in the south of HIIC1 region. The Tashikuer station in the northwest of HIID2 region also exhibited a change similar to that detected at the Henan station, although its TCM trend was not observed to be significant. Overall, our results demonstrate that temperature decline was by no means the dominant trend in the context of climate change on the QTP region. Nevertheless, declines were recorded at several stations; such changes can be attributed to the complex topography of the QTP, where local environmental conditions can have a more pronounced effect on temperature and its variation (Dong *et al.*, 2012). The large increases in TCM were associated with increases in winter temperature on the Tibetan Plateau during the study period; in fact, it has been shown that nighttime temperature can contribute considerably to warming trends in winter (Liu *et al.*, 2006; Wang *et al.*, 2013). Conversely, the relatively small increases in TWM were likely determined primarily by changes in summer temperature. For example, in recent decades, summer temperature increases of approximately $0.022\text{ °C year}^{-1}$ have been recorded for the Tibetan Plateau (Xu *et al.*, 2008); this corresponds to the rate of increase that we obtained for TWM.

Figure 7. Inter-annual variations in (a) accumulated temperature above 0°C and (b) number of days with daily mean temperature above 0°C at regional scale on the Qinghai–Tibetan Plateau during the period 1961–2013. In the figures, straight lines refer to linear trends.

Figure 8. Trends in (a) accumulated temperature above 0°C and (b) number of days with daily mean temperature above 0°C on the Qinghai–Tibetan Plateau during the period 1961–2013.

AT_0 , AT_5 , and AT_{10} were all observed to increase on the Tibetan Plateau during the study period, although AT_0 exhibited the most rapid increase, followed by AT_5 and AT_{10} . This provides further support for the assertion that the temperature increase was more pronounced during the cold seasons than the warm seasons. In contrast to the results found for accumulated temperature, DT_0 increased most rapidly, followed by DT_{10} and DT_5 . Moreover, DT_0 was found to change most significantly, followed by DT_{10} and DT_5 . This indicates that the accumulated temperature on the plateau does not increase with increasing duration of elevated temperatures. The trend in DT was found to be less significant than that in AT, partly because the temperature increase observed at some stations resulted from a higher mean daily temperature in certain months; such increases would not contribute to increases in DT. For instance, some stations recorded a considerable increase in AT_0 but no obvious increase in DT_0 because the daily temperature would have increased not from below zero to above zero but from some value above zero to a higher positive value; such changes would not be reflected in

DT_0 but would have been reflected in accumulated temperatures. Some stations even recorded decreases in DT, although such observations were rare. Our findings in this regard are similar to observations in other regions globally, including Germany (Menzel *et al.*, 2003) and Argentina (Fernández-Long *et al.*, 2013) and more broadly, in the mid- and high-latitudes of the Northern Hemisphere (Frich *et al.*, 2002; Fu *et al.*, 2014). Compared with these regions, AT and DT for the QTP both exhibited greater increases and were more significant. Owing to increases in anthropogenic greenhouse gas emissions, annual temperature has exhibited a prominent increasing trend in recent decades, particularly after 1980 (Lu and Liu, 2010). This accelerated warming trend would have resulted in a rapid increase in both AT and DT. In fact, Liu *et al.* (2010) reported that DT_5 for China as a whole has exhibited a rapidly increasing trend since the 1980s. Dong *et al.* (2012) suggested that the daily minimum temperature in spring (March, April, and May) and autumn (September and October) may have a considerable effect on variations in DT.

The observed increases in TWM and TCM may have helped to overcome low-temperature limitations to plant growth, causing the area of alpine vegetation to shrink and the boundaries of temperate vegetation to move northwards and towards higher altitudes (Zhao *et al.*, 2011). Similarly, Wong *et al.* (2010) reported that recent climate change may have induced advancement of treelines in the southeastern part of the Tibetan Plateau on the basis of a vegetation survey and tree-ring analysis. Additionally, low TWM is typically regarded as a controlling factor of treelines in alpine regions globally (Ohsawa, 1990; Cogbill and White, 1991; Malyshev, 1993). A change in AT can be regarded broadly as a change in the growing season of vegetation. In this context, higher AT indicates a prolonged growing season, which favours the growth of alpine vegetation. For example, on the basis of satellite-derived NDVI data, Piao *et al.* (2011) found that the average onset of vegetation green-up over the QTP advanced by approximately 4.1 days from 1982 to 2006. Prolonging the growing season can further enhance dry matter accumulation, even if precipitation remains the same. Recent experimental warming studies have suggested that warming increased aboveground net primary productivity in the alpine meadow on the Tibetan Plateau (Klein *et al.*, 2007). However, if precipitation were to decrease in this region, the resulting drier and warmer climate would lead to degradation of the alpine vegetation; this has been supported by a simulation study (Zhao *et al.*, 2011). Moreover, the increase in DT_{10} has increased cultivation on the plateau by expanding the cultivable lands towards higher elevations and altering the mix of crops, whereas the change in DT_0 has had a substantial impact on the distribution of glaciers and frozen soil. Increases in DT_0 should act to accelerate melting of glaciers and reduce the duration of frozen soil, thus affecting the balance between water supply and demand, and causing structural and functional changes in plateau ecosystems. For example, Huang *et al.* (2011) suggested that some lakes on the QTP exhibited an expanding trend because of increased recharge of glacier melt water, which led to some flooding of grassland surrounding the lakes. Xue *et al.* (2009) found that warming climate has induced prominent increases of the depth of the seasonal thawing layer in the Three-River Headwater region of QTP, thus inducing drier in the upper soil layer, which caused degradation in some alpine meadow of the QTP.

All the bio-temperature indicators that were considered exhibited increasing trends at different levels, suggesting a potential shift in the ecological niche and changes in the structures and functions of plateau ecosystems. In fact, such changes in plateau ecosystems have been demonstrated by previous studies. However, these changes were observed only in parts of the QTP, not throughout the plateau, suggesting that the plateau ecosystem may be resilient or adapted to climate change. Therefore, it may not be suitable to adopt fixed bio-temperature thresholds in the dynamic vegetation models used to predict changes in ecosystem structure and function for this region. A more applicable scheme must be developed to consider

mechanisms of resilience and adaptation of various vegetation types to climate change. Based on the previous studies investigating changes in precipitation (Yang *et al.*, 2011; Liang *et al.*, 2013), opportunities exist for ecological construction under a changing climate. Accordingly, farmers and policy-makers should take such opportunities to plan agricultural production and implement ecological construction; this would allow sustainable development to be achieved while maintaining a balanced ecosystem.

Some uncertainties remain regarding the limits of the data and methods utilized here. For example, changes in the bio-temperature indicators in the northwest of the plateau, such as in the HID1 region (which covers a particularly large area but contains no observation stations owing to the harsh natural conditions), were not included in this research. The vast area of the QTP, the relatively sparse distribution of meteorological stations, and particularly the diverse spatial distribution of the bio-temperature indicators have presented considerable obstacles to completion of this research. As the major factor limiting plant growth, low temperatures affect the growth of vegetation on the plateau in conjunction with precipitation. However, the interaction between temperature and precipitation is complicated by the high insolation and frequent strong winds on the plateau. Therefore, in future studies, comprehensive indicators must be adopted to ensure a more accurate analysis. Moreover, the broad conditions of the QTP are underrepresented by the data obtained from the existing stations; additional data covering the entire target area would improve the applicability of our results. Thus, it is necessary to develop a highly precise interpolation approach for local or regional ecological research, in accordance with the complex environment of the QTP.

5. Conclusions

All the bio-temperature indicators considered were found to exhibit significant increasing trends across the QTP during the period 1961–2013. In particular, average TWM and TCM at the regional scale exhibited significant rising trends, although changes in TCM were larger in magnitude than those in TWM. Spatially, larger increases in TWM and TCM were concentrated primarily in the Qaidam basin desert and the Guoluo–Naqu alpine shrub meadow regions. The regional average values of AT_{10} , AT_5 , and AT_0 also exhibited increasing trends; of these, AT_0 exhibited the fastest rate and most significant changes, followed by AT_5 and AT_{10} . Similarly, DT_0 exhibited a faster rate of increase than DT_{10} and DT_5 . Spatially, AT and DT exhibited asymmetrical change, where large increases in AT did not correspond to similar large increases in DT.

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