Chinese Science Bulletin

ARTICLES

Spatiotemporal vegetation cover variations in the Qinghai-Tibet Plateau under global climate change

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Empirical Orthogonal Function (EOF) analysis and the related Principal Components (PC) analysis are used to extract valuable vegetation cover derived information from the National Oceanic and Atmospheric Administration (NOAA-AVHRR)'s Leaf Area Index (LAI) satellite images. Results suggest that from 1982 to 2000 global climate change has contributed to an increase in vegetation cover in the Qinghai-Tibet Plateau. The correlation between rainfall and LAI EOF PC1 and PC2 indicates that rainfall is the major climatic factor influencing interannual variations of average vegetation cover throughout the entire Plateau. However, annual mean vegetation cover trends in the Qinghai-Tibet Plateau are mainly out of phase with air temperature increasing, which is primarily responsible for nonsynchronous changes of vegetation cover. In the southern ridge of the Qinghai-Tibet Plateau, recent warming trends contribute to humid weather and favorable conditions for vegetation growth. By contrast, higher temperatures have led to arid conditions and insufficient rainfall in the northern part of the Plateau, leading to drought and other climatic conditions which are not conducive to increased vegetation cover.

Qinghai-Tibet Plateau, LAI, Empirical Orthogonal Function (EOF), climatic factor

Lying to the north of the Himalayas in Central Asia, large swaths of the Qinghai-Tibet Plateau are uninhabited, leading to fewer human influences than in other regions of China. Significant air and land surface temperature increases have been observed on the Qinghai-Tibet Plateau, in particular during the spring and winter[1−3]. Since the 1970s, the global climate change has contributed to a decrease in the coverage and depth of frozen earth in the Qinghai-Tibet Plateau[4] and climatic zone adjustments[5]. Land surface thermodynamics and fluxes have significantly influenced regional climate in China since the 1980s[6]. For example, enhanced surface albedo fluctuations caused by land surface changes can profoundly influence land surface properties, leading to pronounced changes to surface radiation and thermal distribution balances. As a result, temperature, pressure, wind, rainfall and other climatic variables in the Qinghai-Tibet Plateau and other regions have adapted to environmental change. These adjustments may significantly affect not only the East Asian Monsoon but also summer rainfall in Yangtze River Valley, leading to hazardous weather conditions[7−12].

As vegetation adapts to regional and global climate change, long-term interactions between vegetation and the environment lead to spatial changes in the distribution of plant species, as well as temporal phenological changes. Dynamic ecosystem models can capture the complex interaction between plant physiological processes and climate variability[13−19]. Gradually increasing

Received August 23, 2007; accepted December 13, 2007
doi: 10.1007/s11434-008-0115-x
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Supported by the National Basic Research Program of China (Grant No. 2006CB403607), the National Natural Science Foundation of China (Grant Nos. 40675047 and 40605023), the Key Project of the Chinese Academy of Sciences (Grant No. KZCX2-YW-219), and a Western Washington University summer research grant

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temperatures due to global warming are having a pronounced effect throughout the Qinghai-Tibet Plateau. In some regions, the perennially frozen earth is decreasing rapidly and the desert area is enlarging while vegetation cover shows a decreasing trend[20−24]. In other regions, vegetation cover is increasing[25,26]. As a result, land surface properties in the Qinghai-Tibet Plateau have become less uniform, leading to more frequent rainfall in eastern China and profound changes in atmospheric circulation and temperature[27,28].

While species diversity arises through adaptation to regional climate, a lack of geographic observational data on the Qinghai-Tibet Plateau has made it difficult to study the spatial distribution and annual variations of vegetation cover. While increasing air temperature trends have been observed for more than 20 years, it is unclear how global climate change impacts spatial-temporal vegetation cover changes in the Qinghai-Tibet Plateau. Accordingly, NOAA-AVHRR derived LAI data are used to investigate spatial-temporal vegetation cover variations on the Qinghai-Tibet Plateau. Specifically, climatic factors are examined in order to reveal the causes which are most responsible for variations to vegetation cover.

1 Data sources and the spatial distribution of land surface properties for the Qinghai-Tibet Plateau

The Qinghai-Tibet Plateau is located in a climatic region which is subdivided into four sub-climate divisions in order to describe temperature and rainfall characteristics as accurately as possible[29]: the Humid South Plateau (H_1), the Sub-humid South Plateau (H_2), the Sub-dry South Plateau (H_3) and the Dry South Plateau (H_4). Air temperature and rainfall patterns lead to an asymmetric distribution of frozen earth on the Qinghai-Tibet Plateau (Figure 1(a)). The spatial distribution of land cover is shown (Figure 1(b)). A correlation analysis based on NOAA-NDVI satellite data (with an 8 km×8 km resolution) clearly identifies four vegetation phenology regions (Figure 1(c)). Longer periods of snowfall and snow cover occur in the Qinghai-Tibet Plateau than in other regions at a similar latitude, thereby impacting the spatiotemporal heterogeneity of land surface properties (Figure 1(d))[32].

There are two factors which make it difficult to analyze the interannual variations of the vegetation cover in the Qinghai-Tibet Plateau: (1) the asymmetric spatiotemporal distribution of land cover and physical features and (2) the temporal variations of vegetation phenology. In particular, large variations in land cover types (often with markedly different properties) occur each month due to frequent snowfall and snow melt. Accordingly, NDVI data is not suitable for identifying interannual vegetation cover variations. Few studies have directly used NDVI data to investigate vegetation cover changes in light of these challenges. Previous work dealing with vegetation cover change on the Qinghai-Tibet Plateau have been not been conclusive and accordingly, it is valuable to further examine results for this region using new techniques[33,34]. Specifically, the LAI (leaf area index) is used to analyze spatiotemporal vegetation cover changes in the Qinghai-Tibet Plateau. The LAI technique can reduce ambiguities resulting from the impact of non-vegetation information such as snow cover on the surface reflectance spectrum. The acquisition of LAI data is based on statistical findings from the global vegetation reflectance spectrum[35]. Moreover, our proposed retrieval method is valuable for applied climate research such as analyzing interannual variations in vegetation cover.

Using 1982—2000 NOAA-AVHRR remotely-sensed data, we analyze a maximum LAI ten day interval time series at an 8 km×8 km resolution. However, it is difficult to contrast seasonal LAI changes at a specific site with others due to out of phase vegetation phenology and extreme weather events which influence vegetation cover. We use each year's maximum monthly LAI value as the yearly vegetation cover index. The maximum monthly LAI approach has a number of advantages, including the ability to capture optimal vegetation cover conditions, the capacity to remove out of phase vegetation phenology, and vegetation cover fluctuations caused by extreme weather events during the vegetation growth.

2 Spatiotemporal vegetation cover changes for the Qinghai-Tibet Plateau

Empirical orthogonal function (EOF) analysis is used to investigate spatiotemporal vegetation cover changes in the Qinghai-Tibet Plateau. EOF is a statistical method for the spatiotemporal decomposition of a signal or data set. It is to decompose two dimensional matrixes $F(t, n)$ with a time scale T and a spatial scale n into the multi-

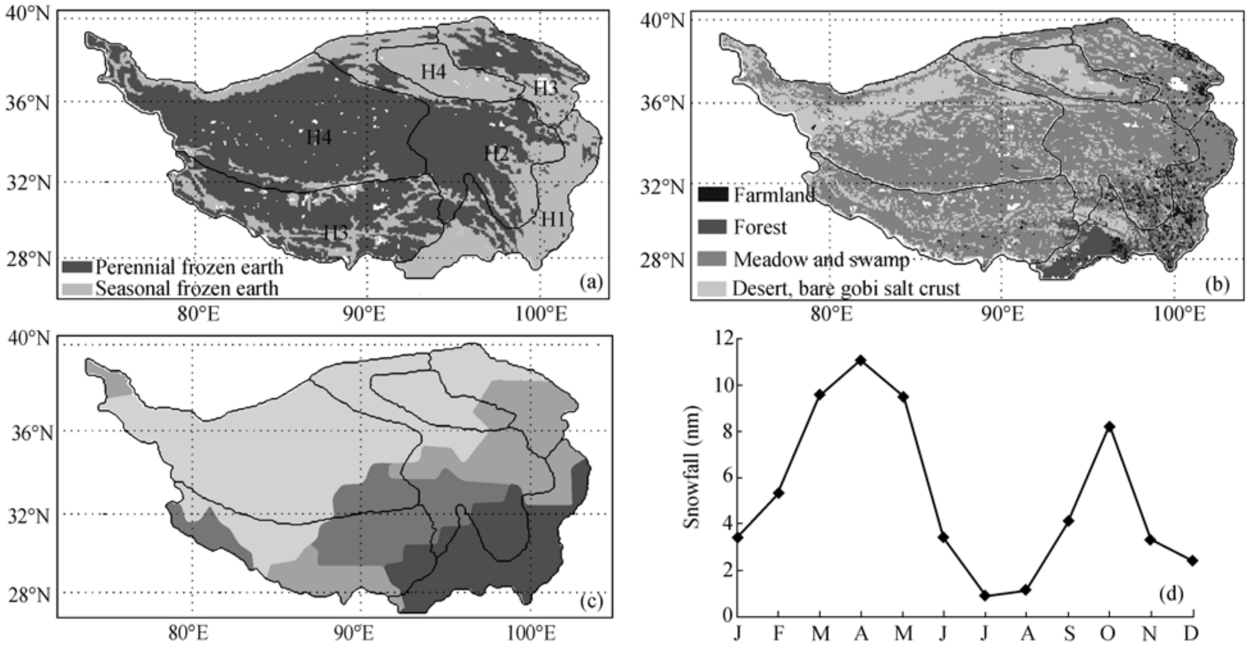

Figure 1 (a) Distribution of frozen earth in the TB[30]; (b) distribution of land cover type in the TB[31]; (c) distribution of vegetation phenology variations in the TB; (d) monthly snow fluctuations based on weather station observational data from 1970 to 2000.

plication of a weighted temporal matrix T and an eigenvector matrix X:

$$F_{ij} = \sum_{k=1}^{n} T_{ik} X_{kj}. \quad (1)$$

That is, a data set $F(t, n)$ can be approximatively expressed in terms of primary eigenvectors and corresponding temporal weighting coefficients. By analyzing these eigenvector and temporal weighting coefficients, the temporal and spatial changes of $F(t, n)$ can be expressed. For a data set $F(t, n)$ undergoing stable temporal changes, the temporal trends are reflected in the first eigenvector while the remaining eigenvectors reflect local changes.

The first and second EOF modes identify the major signals from LAI data set (Table 1). The first eigenvector, representing the overally trend of vegetation cover change throughout the plateau shows almost all positive values and accounts for 50.4% of the total variance (a higher percentage than the variance individually explained by any of the other eigenvectors). The center of maximum value for the first eigenvector is located in the Humid South Plateau (H_1)(Figure 2(a)), implying that the annual vegetation cover trend is dominated by the trends and status of vegetation cover in the southern region of plateau. Since other regions have less vegetation cover than the Humid South Plateau, it is difficult to analyze how vegetation cover change impacts the entire plateau.

Total LAI change is composed of the first eigenvector (representing overall average vegetation cover change) and other eigenvectors (which reflect regional differences in vegetation cover change). The second eigenvector accounts for 11.9% of the total variance (which accounts for most of the regional difference observed in the vegetation cover change). The spatial distribution of the second eigenvector shows that an increase in vegetation cover in one part (i.e. southern region) of the Qinghai-Tibet Plateau will lead to a decrease in the vegetation cover in another part (i.e. the northern part) (Figure 2(b)). This phenomenon is prominent in middle-eastern regions of the plateau.

The first and second PCs reflect the interannual variability of their respective eigenvectors. Both the first and second PCs show a large interannual variability and

Table 1 The percentage of variance explained by the eigenvectors using EOF expansion of maximum annual LAI

Serial number	1	2	3	4	5	6	7	8	9	10
Eigenvectors	7.54	1.78	1.29	0.93	0.72	0.52	0.43	0.36	0.28	0.23
Variance	50.4	11.9	8.6	6.2	4.8	3.5	2.9	2.4	1.9	1.5

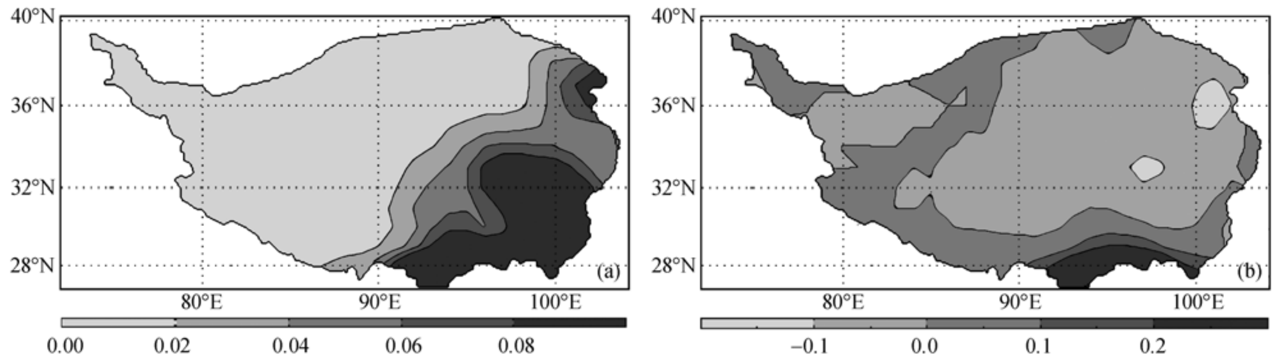

Figure 2 Distribution of the first eigenvector (a) and the second eigenvector (b) decomposed LAI data set by EOF on the Qinghai-Tibet Plateau.

linearly increasing trends (Figure 3), suggesting that the averaged vegetation cover ratio is increasing, especially in the south region of plateau. However, this enlarges the vegetation cover ratio between the southern and northern plateau regions.

3 Impacts of climate-driven variables on vegetation cover

Remote sensing data includes vegetation cover information which is influenced by both climate variables and human activities. The Qinghai-Tibet Plateau is relatively undisturbed due to low population densities and hence vegetation cover and ecosystem changes are primarily controlled by the climate system. Precipitation and temperature are two major climatic factors which affect vegetation cover and ecosystem changes. Precipitation provides water for vegetation growth and with sufficient precipitation (in the absence of temperature anomalies), a positive correlation exists between the vegetation cover ratio and precipitation. In arid regions, vegetation is quite sensitive to precipitation, and hence a negative correlation exists between the vegetation cover ratio and temperature. In contrast, for regions with sufficient precipitation, temperature is the primary factor limiting vegetation growth, and the influence of precipitation on vegetation growth is less important[36].

From the 1970—2000 observation data, the statistical results show relatively stable precipitation levels with a slight decreasing annual mean precipitation trend during the mid-1990s in the Sub-dry South Plateau (H_3). Annual mean temperature, however, increases significantly in all four climate divisions. Beginning in the 1990s, the warming temperature trend becomes more significant (Figure 4). Therefore, the distributions of eigenvectors and PC changes from the decomposed LAI by EOF have a close relationship with temperature increases.

A correlation between the annual mean LAI and precipitation anomaly is calculated (Figure 5(a)). The cor-

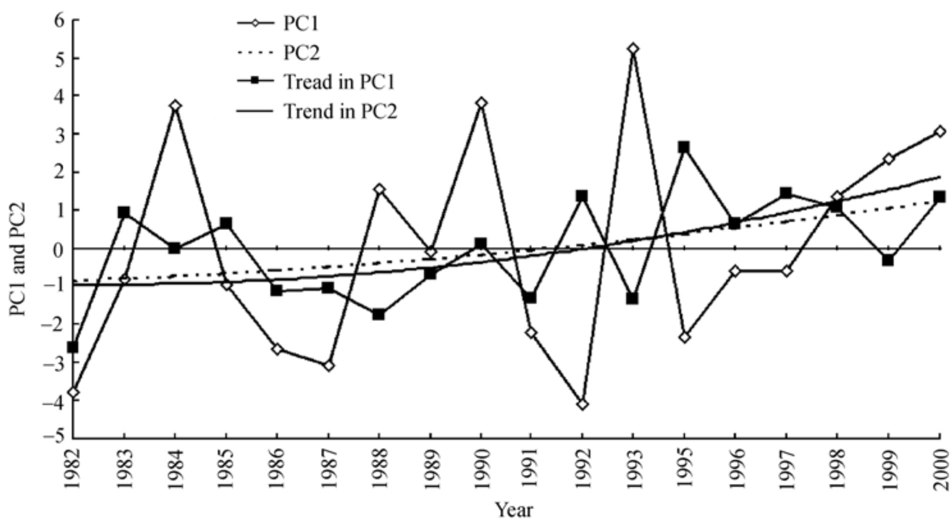

Figure 3 First and second PCs of EOF for LAI corresponding to eigenvectors.

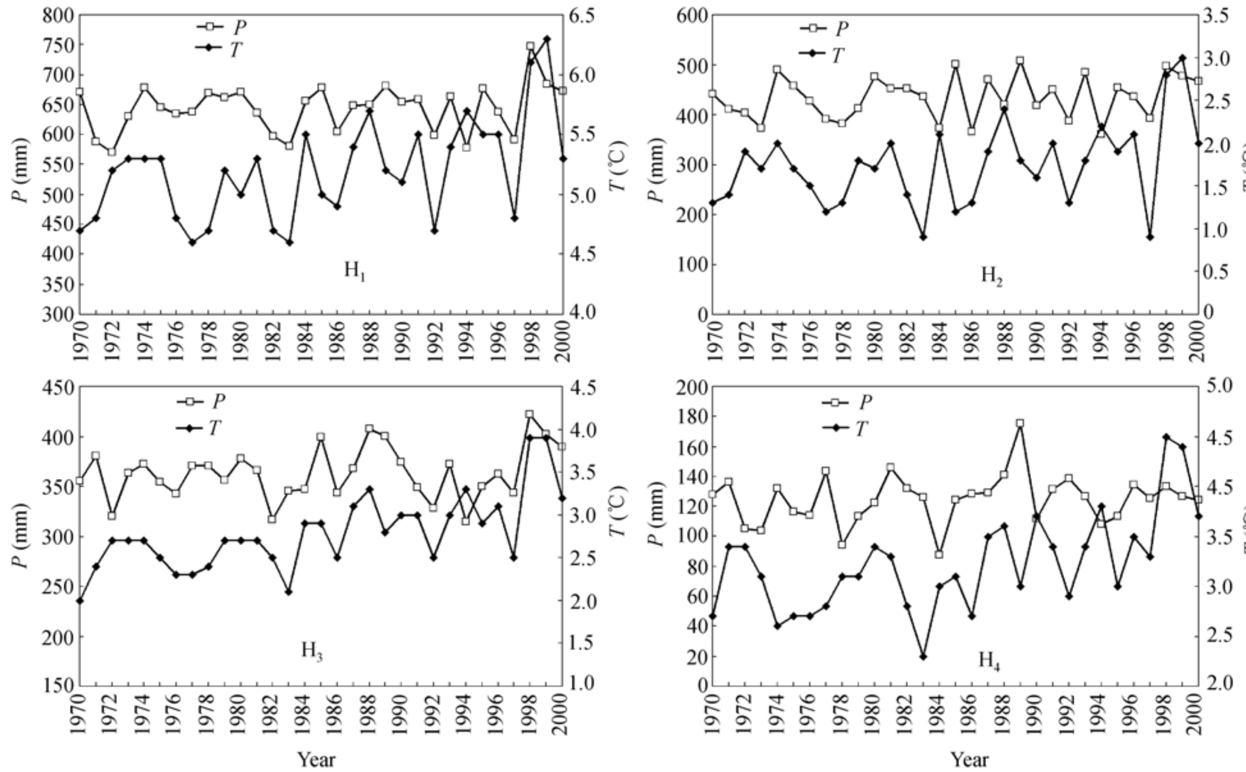

Figure 4 Annual mean precipitation (P) and temperature (T) in the Humid South Plateau (H_1), the Sub-humid South Plateau (H_2), the Sub-dry South Plateau (H_3) and the Dry South Plateau (H_4) from 1970 to 2000.

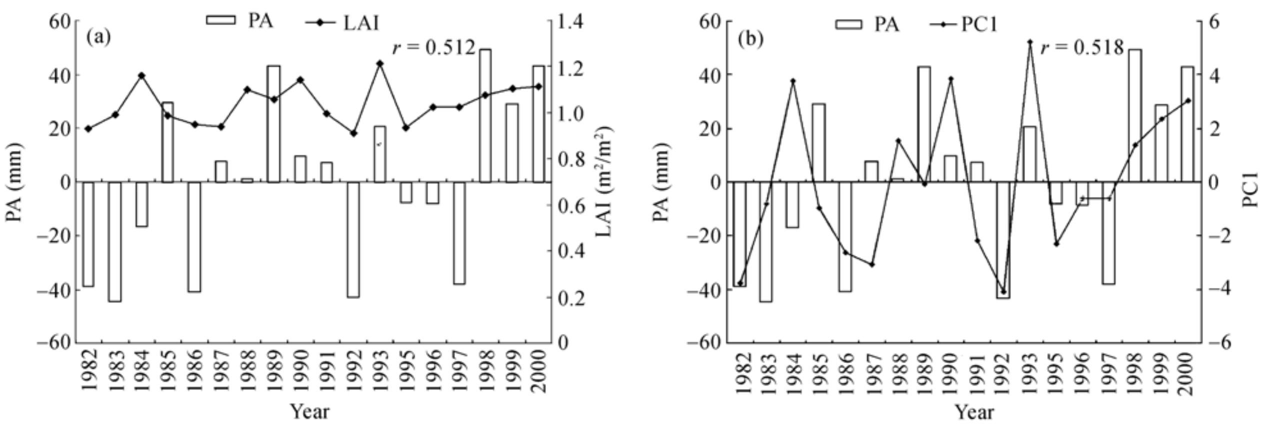

Figure 5 Precipitation anomalies (PA) and annual mean LAI (a), and the first PC of EOF for LAI (b) from 1970 to 2000.

relation coefficient (r) is 0.512 at the 95% significance level (more than 0.468). Since the LAI PC1 (for EOF) represents the changing trend of average LAI across the entire plateau region, the correlation between PC1 and precipitation anomaly is 0.518, at the 95% significance level (Figure 5(b)). However, a significant correlation was not observed between precipitation anomalies and other PCs. The significant correlations between precipitation anomaly and LAI as well as between LAI PC1 (for EOF) suggests that annual mean vegetation cover fluctuations for the entire plateau region is mainly controlled by precipitation, and the regional vegetation cover difference is not related to precipitation. Accordingly, other meteorological factors are likely responsible for the regional difference of vegetation cover.

Two pieces of evidence support this hypothesis. First, a significant correlation was not found between annual mean temperature and the first or second PC. Second, the spatial distribution of the correlation between annual mean temperature from 1°×1° resolution observation data and annual mean LAI confirms that the effects of temperature on vegetation are a primary reason for the lack of a significant correlation between overall annual mean temperature and annual mean LAI on the Qinghai-Tibet Plateau (Figure 6). The climate of the northern part of the plateau is arid and semi-arid, with an annual mean precipitation of approximately 240.8 mm. Accordingly, temperature increases cause additional evaportanspiration from the land surface. Vegetation growth is limited by severe aridity, causing a negative correlation coefficient. In contrast, in the humid and subhumid southern plateau, precipitation is sufficient, and annual mean precipitation reaches 535.4 mm. The correlation coefficient shows the positive value as a result of increasing temperature which is favorable for vegetation growth.

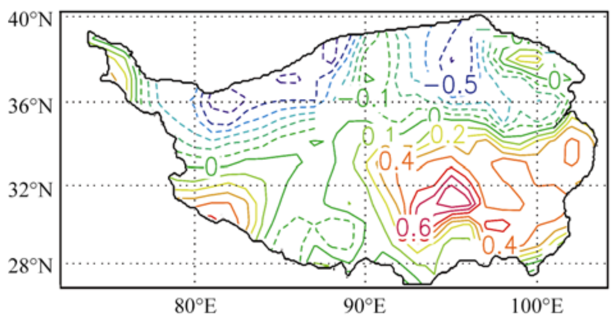

Figure 6 The distribution of the correlation coefficient between LAI and temperature.

The distribution of the second eigenvector (Figure 2(b)) is now compared with the spatial distribution of the correlation coefficient between LAI and temperature (Figure 6). The distribution of the second eigenvector's negative value is found to be generally consistent with the negative correlation. Similarly, the distribution of the positive value in the second eigenvector is also consistent with the positive correlation. The spatial consistency of the climate scale suggests that temperature is responsible for the seasaw pattern of vegetation cover in the southern and northern regions of plateau. In the northern sections of the plateau, scant precipitation along with increasing temperatures exacerbates drought conditions, leading to restrained vegetation growth. While southern regions of the plateau have sufficient precipitation, increasing temperatures lead to more vegetation cover. Due to stable annual mean precipitation values in four climate divisions, it follows that increasing temperature (rather than precipitation) is the primary cause of the observed vegetation cover changes in the Qinghai-Tibet Plateau.

4 Conclusions and discussion

The impact of climate and other natural factors is an important component of vegetation growth and ecosystem dynamics. The Qinghai-Tibet Plateau represents an ideal area to study interaction between climate and vegetation cover due to the complicated climate regime as well as a low population density (and limited human activities). By analyzing precipitation and temperature conditions that affect vegetation growth, it is shown that climate divisions on the Qinghai-Tibet Plateau results in spatio-temporal regional land cover characteristics. Vegetation cover changes from 1980—2000 are associated with increasing temperature. In the southern regions of the plateau, vegetation cover in Humid South Plateau(H_1)plays a critical role, influencing the annual mean vegetation cover trend for the entire plateau. On the one hand, the higher temperatures observed in the southern Qinghai-Tibet Plateau lead to longer plant growing periods, and an expansion of vegetation. However, it is known that vegetation water requirements also increase with rising temperatures and expanding vegetation cover. Accordingly, a decrease in precipitation in the Humid South Plateau (H_1) would contribute to degraded vegetation cover as temperatures rise.

Vegetation cover and ecosystems possess the ability to adapt to the combined impact of changes in various climate elements, although vegetation growth flourishes most when a balance among climate elements is achieved. Important conclusions of this paper are provided below:

(1) From the early 1980s to 2000, vegetation cover on the Qinghai-Tibet Plateau follows an increasing trend. A significant percentage of the vegetation is located in the humid southern region of the plateau, where vegetation cover change plays a decisive role in the ecology of the entire plateau area. Specifically, increasing vegetation cover in the humid south region of the plateau is driving the observed increases in vegetation cover throughout the entire plateau.

(2) Climate warming is responsible for the annual vegetation cover changes which exhibit the observed seasaw pattern between the southern and northern regions of the Qinghai-Tibet Plateau. Higher cumulative temperatures are advantageous for vegetation growth

and ecosystem development in the humid southern region of this plateau. On the other hand, in the arid or semi-arid northern regions of plateau, a degradation in vegetation cover is observed. This is particularly true around the Sub-dry South Plateau (H_3) where vegetation cover is relatively dense. In the northern regions of the plateau, increasing temperatures significantly impact vegetation growth. Finally, vegetation degradation associated with a slight decrease in precipitation was observed during the mid-1990s in the northern plateau region.

(3) Both temperature and precipitation are climate-driven factors that cause regional vegetation cover differences on the Qinghai-Tibet Plateau. Specifically, the precipitation dominates annual vegetation cover changes and drought becomes more severe with increasing temperatures in the northern regions of the plateau. As a result, increased vegetation growth requires more precipitation. Meanwhile, it also causes a longer vegetation growth period and a higher vegetation cover ratio in the humid southern regions of the plateau, and the vegetation requires more water (similar to the water needs of the arid northern plateau). Therefore, a positive correlation exists between precipitation and total vegetation cover on the Qinghai-Tibet Plateau due to rising temperatures.

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