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Elevation-dependent relationships between climate change and grassland vegetation variation across the Qinghai-Xizang Plateau

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ABSTRACT: As one of the most sensitive regions to climate change, the Qinghai-Xizang Plateau has been widely investigated as one unity for impacts of climate change on alpine grassland. However, previous findings might be confounded by distinct climate sensitivities at different elevations and different regional climates between Qinghai Province and Xizang Province, which lie at the two sides of Tanggula Mountains. In this study, we explored change trends of grassland vegetation, temperature and precipitation in growing season from 1982 to 2011, and elevation-dependent effects of climate change on grassland vegetation in the two provinces separately. The plateau grassland greenness gained improvement under climate warming and wetting during the past 30 years, especially in Qinghai Province. Temperature increased significantly with a warming magnitude of more than 1.5 °C over the plateau grassland. The interannual change of precipitation showed contrary trends between the two provinces. The main climate factor driving the grassland vegetation variation varied between the two provinces, with temperature being the main factor in Qinghai Province and precipitation being the main factor in Xizang Province. In particular, a more significant correlation between climate change and grassland vegetation variation was found at higher elevations, which reveals higher climate sensitivity in higher elevation areas of the plateau.

1. Introduction

Climate change has brought widespread effects on global vegetation ecosystem (Walther *et al.*, 2002; Parmesan and Yohe, 2003; Tao *et al.*, 2013a). The effects are suggested to have strong spatial variability in regions that are sensitive to climate change (Myneni *et al.*, 1997; Zhou *et al.*, 2001; Gerten *et al.*, 2004; Piao *et al.*, 2006a; Piao *et al.*, 2011a). Both instrumental observations and model simulations have tracked an enhanced recent climate change in high elevation mountains (Beniston *et al.*, 1997; Giorgi *et al.*, 1997; Pepin and Lundquist, 2008), such as the Qinghai-Xizang Plateau (Liu and Chen, 2000; Kang *et al.*, 2010).

The Qinghai-Xizang Plateau, synonymous with the Tibetan Plateau, is the highest and largest plateau in the world. The plateau is assigned a crucial role in shaping Asian climate. The plateau exerts a powerful thermal influence on the Asian climate system (He *et al.*, 1987;

Smith and Shi, 1992; Yanai and Li, 1994; Wu *et al.*, 2012). The extensive plateau surface acts as a heating source to impact energy flux between land and atmosphere (Guo *et al.*, 2011; Yang *et al.*, 2011a; Zhu *et al.*, 2012). The thermal influence is much stronger in the southern plateau than in the northern plateau because the largest heating source lies in the south of the plateau (Yanai and Li, 1994; Molnar *et al.*, 2010).

On the other hand, the plateau is located at the northern and western periphery of the South Asian monsoon and the East Asian monsoon, respectively, and therefore acts as an obstacle to the Asian monsoon. The high terrains of the plateau not only affect the South Asian monsoon by preventing cold and dry extra-tropical atmosphere from convecting with warm and moist tropical air masses (Chou *et al.*, 2001; Privé and Plumb, 2007; Boos and Emanuel, 2009), but also play an unnegligible role in influencing the East Asian monsoon by altering eastward westerly jet (Liang and Wang, 1998; Xie *et al.*, 2006; Wu *et al.*, 2007). Shaped by local topography, water vapour sources supplying to the plateau is divided into three routes, i.e. the Arabian Sea and Bay of Bengal, the South China Sea, and the mid-latitude westerly (Simmonds *et al.*, 1999; Wang

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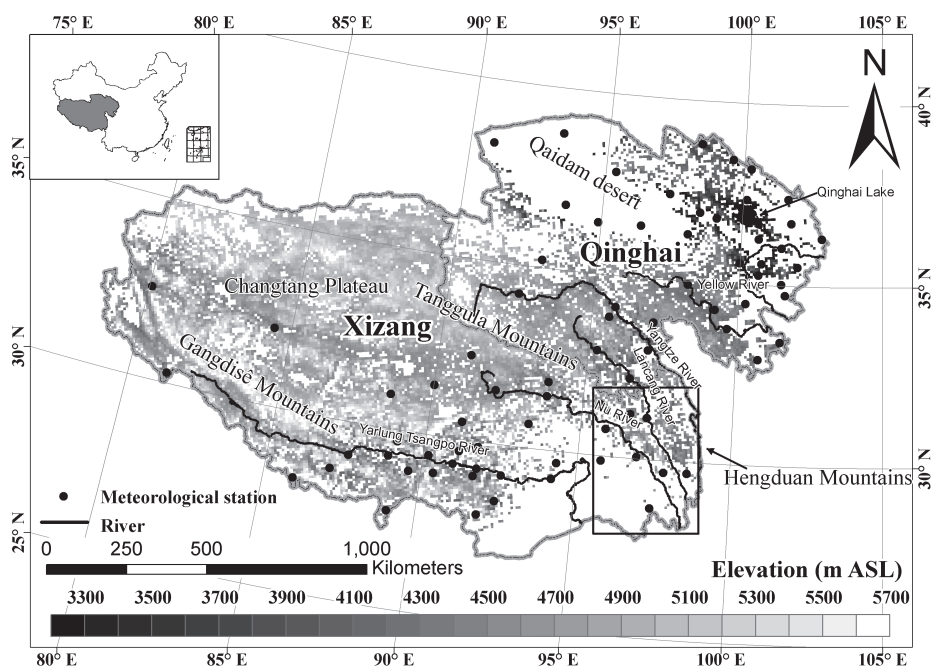
Figure 1. Map of the Qinghai-Xizang Plateau. Black dots denote locations of meteorological stations; solid lines denote rivers.

and Fan, 1999). The water vapour source of the South Asian monsoon originates from the Arabian Sea and Bay of Bengal, and dominates the summer precipitation over the southern plateau (Fu *et al.*, 2006; Feng and Zhou, 2012; Yang *et al.*, 2014a). For the East Asian monsoon, the water vapour transported from the South China Sea converges with the subtropical anticyclone from the West North Pacific in southern China, and then collocates with the mid-latitude westerly and turns northeastwards in the northeastern plateau (Chen *et al.*, 2000; Zhao and Chen, 2001; Duan and Wu, 2005; Li *et al.*, 2010; Wu *et al.*, 2012).

A plenty of studies have investigated climate change in the plateau during the late half of the 20th century using ground meteorological records (Liu *et al.*, 2006; You *et al.*, 2008; Rangwala *et al.*, 2009), remote sensing data (Qin *et al.*, 2009; Tao *et al.*, 2013b), climate model (Chen *et al.*, 2003; Yang *et al.*, 2011b; Yin *et al.*, 2013), and reanalysis products (Frauenfeld *et al.*, 2005; You *et al.*, 2010; Feng and Zhou, 2012; Wang and Guo, 2012). The entire plateau has experienced an overall climate warming and wetting trend since the 1980s. However, such climate change showed evident spatial heterogeneity, with more obvious warming and wetting over the northern plateau (Yang *et al.*, 2011b; Yin *et al.*, 2013), especially at higher elevations (Liu *et al.*, 2006; Arakawa and Kitoh, 2012; Rangwala and Miller, 2012). In contrast, precipitation decreased over the southeastern plateau (Liu *et al.*, 2009a; Yang *et al.*, 2014a). This contradictory precipitation trend is attributed to different water vapour sources, and different terrain and topography between the northern and the southern plateau (Chen *et al.*, 2012; Wang and Guo, 2012; Yang *et al.*, 2014a). Numerous studies further indicated that such contrast is more obvious between the

two sides of the Tanggula Mountains (Zhang *et al.*, 2004; Yang *et al.*, 2006, 2007a; Liu *et al.*, 2008).

The Tanggula Mountains divide the plateau into two unique and independent geographical units as Qinghai Province and Xizang Province in the northeastern and southwestern plateau, respectively (Figure 1). Regional atmospheric circulation is influenced by the existence of the mountains and consequently generating different climate characteristics between the two sides, especially for precipitation. In Qinghai province, water vapour is carried by the East Asian monsoon and mid-latitude westerly converge in the confluent region of the northeastern plateau (Chen *et al.*, 2000; Xu *et al.*, 2008; Wu *et al.*, 2012). In Xizang Province, water vapour is carried by the South Asian monsoon through the middle Himalaya and the southeastern part of the province to the northwestern plateau (Yang *et al.*, 2007b; Feng and Zhou, 2012; Wang and Guo, 2012). The southeastern Xizang Province is wet due to the vapour obstruction by the Tanggula Mountains. The northward water vapour carried by the South Asian monsoon can barely reach the north side of the Tanggula Mountains (Feng and Zhou, 2012; Wang and Guo, 2012).

The dramatic climate change has resulted in corresponding vegetation variation in the plateau based on region-scale remotely sensed analyses (Yang and Piao, 2006; Gao *et al.*, 2010; Piao *et al.*, 2011a; Cong *et al.*, 2013; Shen *et al.*, 2014) and model simulation (Yang *et al.*, 2008; Zhong *et al.*, 2010; Ni and Herzschuh, 2011; Zuo *et al.*, 2011; Piao *et al.*, 2012). The grassland vegetation response to climate change shows obvious elevational and spatial patterns. Using normalized difference vegetation index (NDVI), remotely sensed studies found enhanced grassland vegetation greenness in the plateau during 1982–2000, followed by grassland degradation

and productivity reduction during 2000–2006 (Piao *et al.*, 2006a; Gao *et al.*, 2009; Gao *et al.*, 2010). The degradation trend was more obvious in the northwestern high elevation plateau (Changtang Plateau). A widespread advanced phenological onset date and delayed phenological end date were also tracked by remote sensing data (Shen *et al.*, 2011; Cong *et al.*, 2013; Che *et al.*, 2014; Shen *et al.*, 2014). In particular, the phenological onset and end dates both occurred earlier along increasing elevations over the plateau. Model simulations revealed different driving factors on grassland net primary productivity (NPP) between the two provinces (Gao *et al.*, 2009; Fan *et al.*, 2010; Piao *et al.*, 2012), with temperature being the main factor in Qinghai Province and precipitation being the main factor in Xizang Province.

Previous studies on climate change, vegetation activity and their relationships usually treated the plateau as one single unity. However, these studies could be confounded by elevational and regional climate heterogeneities, which can complicate vegetation response to climate change on the plateau (Chang, 1981; Tao *et al.*, 2013b). Similar elevation-dependent responses of vegetation to climate have already been reported (Wang *et al.*, 2007; Lu *et al.*, 2008; Piao *et al.*, 2011a; Shen *et al.*, 2014). On the other hand, climate regime and its effects on grassland vegetation exhibit evident differences between Qinghai Province and Xizang Province. The above-mentioned confounding factors reveal that the response of the plateau grasslands to climate change needs to be further explored in a more spatially specific manner. In particular, Qinghai Province and Xizang Province need to be treated as separate units. To this end, we used a 30-year long-term NOAA/AVHRR NDVI dataset to examine vegetation response to climate change at each elevation bin by treating Qinghai Province and Xizang Province separately. Specifically, we addressed the following questions:

(1) How have the plateau grassland vegetation and climate changed during 1982–2011?
(2) How did the change trends of grassland vegetation, climate, and the relationships between them vary along the elevation bins and between the two provinces?

2. Data and methods

2.1. Study area

The Qinghai-Xizang Plateau, located in southwestern China, is known as 'the roof of the world' with an average elevation of more than 4000 m above sea level (ASL) (Figure 1). The plateau plays an important role as the headwater region of major rivers in Asia, and as habitats for endangered wildlives. Alpine grasslands, including alpine meadow and steppe, are the dominant vegetation type on the plateau (Editorial Board of Vegetation Map of China, 2001). The plateau is composed of two geographical units of Qinghai Province and Xizang Province with Tanggula Mountains in between. Between the two provinces, the topographical characteristics are different (Figure 1). In Qinghai Province, the elevation grows higher from the northeastern foot to the same-side peak gradually and the elevation gradient is relatively simple. In Xizang Province, elevation increases from low to high along numerous mountains (e.g. Gangtise Mountains, Himalaya Mountains and the Changtang Plateau), forming several humps.

In the plateau, temperature is higher at low elevations of northeastern Qinghai Province and southeastern Xizang Province (Figure 2(a)). The warmest and coldest months are July and January, respectively. The averaged daily precipitation decreases from east to west in Qinghai Province and from southeast to northwest in Xizang Province, respectively (Figure 2(b)). The spatial climate gradients are different between the two provinces (Figure 2(c)). In Qinghai Province, the northern grasslands are located in the temperate zone, while southern grasslands are situated in the sub-arctic zone. The eastern and southeastern grasslands are fed by sub-humid/humid climate, but the northwestern grasslands feature a semi-arid/arid/extreme arid climate. In Xizang province, grasslands are mostly distributed in sub-arctic/arctic zone with semi-arid/arid climate. Accordingly, the growing season grassland NDVI (GSNDVI) decreases from east to west in Qinghai Province and from southeast to northwest in Xizang Province (Figure 2(c)). The highest grassland GSNDVI was observed in the warm and wet eastern Qinghai Province and southeastern Xizang Province, while the lowest grassland GSNDVI was detected in the northwestern Qinghai Province and the northern Xizang Province.

2.2. Data

The AVHRR NDVI dataset derived from the Global Inventory Modelling and Mapping Studies (GIMMS) was used in this study. This dataset is the longest running series of NDVI products suitable for large-scale ecological studies (Tucker *et al.*, 2005). The earlier version of this dataset (i.e. GIMMS 1982–2006) has been intensively used in exploring the relationship between vegetation variation and climate change at regional scales (Nemani *et al.*, 2003). To date, the third generation of the GIMMS (GIMMS3g) dataset, a new 30-year continuous series of NDVI dataset with a spatial resolution of 8 km × 8 km and a temporal resolution of a half-month interval from 1982 to 2011 has been released. The dataset was produced with AVHRR sensors from NOAA 7 to 18 satellites and proved to be highly comparable with MODIS and SPOT data (Fensholt *et al.*, 2009; Fensholt and Proud, 2012; Howard *et al.*, 2012; Zhu *et al.*, 2013), and has been used widely in China and the Qinghai-Xizang Plateau (Cong *et al.*, 2013; Che *et al.*, 2014; Shen *et al.*, 2014). In this study, we only used grassland NDVI data in growing season, which is equal to the period from May to September (Piao *et al.*, 2011a).

Climate data was derived from the China Meteorological Administration (CMA), which maintains 78 meteorological stations in the Qinghai-Xizang Plateau. We selected daily mean temperature and daily total precipitation records from 1982 to 2011 and aggregated them

Figure 2. Spatial patterns of growing season temperature (GST) (a), growing season precipitation (GSP) (b), and growing season NDVI (GSNDVI) (c) of the plateau grassland. In panel (c), tropical (IA)/sub-tropical (IIA) humid climate, alpine temperate humid (HIIIA)/semi-humid (HIIIB)/semi-arid (HIIIC)/arid (HIIID)/extreme arid (HIIIE) climate, alpine sub-arctic humid (HIVA)/semi-humid (HIVB)/semi-arid (HIVC)/arid (HIVD) climate and alpine arctic semi-arid (HVC)/arid (HVD) climate.

to a half-month average to match the temporal resolution of the GIMMS3g NDVI dataset. The aggregated climate data were interpolated to spatially continuous ones and then re-aggregated to growing season average temperature (GST) and growing season average precipitation (GSP) with an 8 km × 8 km spatial resolution. We used the thin-plate smoothing splines interpolation method of the ANUspline software (Hutchinson and Dowling, 1991). The ANUspline software has been proven to have a higher accuracy in mountain areas than other interpolation

methods because it includes elevation as a covariate into the interpolation process (Hutchinson, 1995).

We used land cover data from the Data Center of Resources and Environmental Sciences, Chinese Academy of Sciences as the baseline map to define the grassland distribution (Liu *et al.*, 2005; Dong *et al.*, 2009). The Shuttle Radar Topography Mission (SRTM) digital elevation data with a 90 m × 90 m spatial resolution were aggregated to an 8 km × 8 km resolution to match other datasets. We took the mean values of GSNDVI, GST and GSP at each 100-m elevation bin during 1982–2011 to analyse the elevation-dependent climate change, vegetation variation and their relationships. To avoid anomalous fluctuation caused by inadequate pixels, we excluded elevation bins whose pixel amounts were less than 100, which resulted in elevation bins from 3200 to 5200 m ASL in Qinghai Province and from 4100 to 5700 m ASL in Xizang Province being included in this study (Figure 1). Pixels above 4500 m ASL occupy a much higher percentage in Xizang Province than in Qinghai Province.

2.3. Methods

We first calculated the change trends of GSNDVI, GST and GSP, and then computed the standardized regression coefficients between GSNDVI and GST, and GSP at each elevation bin in the two provinces separately. The change trends of GSNDVI, GST and GSP were defined as their linear regression slopes against time. We also divided the change trends of GSNDVI by an averaged GSNDVI value during 1982–2011 to calculate their change percentage at each elevation bin. Second, we calculated the standardized regression coefficients of GST and GSP to evaluate which has the main effect on GSNDVI variation by using a linear regression model (Bring, 1994):

$$\frac{y - y_{\text{mean}}}{\text{SD}_y} = a + b_1 \frac{x_1 - x_{1\text{mean}}}{\text{SD}_{x_1}} + b_2 \frac{x_2 - x_{2\text{mean}}}{\text{SD}_{x_2}} \quad (1)$$

where y is a value array of GSNDVI at an elevation bin during 1982–2011; y_{mean}, the mean value of y; SD_y, the standard deviation of y; x_1, x_2 are the value arrays of GST and GSP at the same elevation bin as y during 1982–2011; $x_{1\text{mean}}$, $x_{2\text{mean}}$ are the mean values of x_1, x_2; SD_{x1}, SD_{x2} are the standard deviations of x_1, x_2; a, the intercept; and b_1, b_2 are the standardized regression coefficients.

3. Results

3.1. Interannual change of grassland GSNDVI, GST and GSP

The interannual change slopes of the spatially averaged grassland GSNDVI, GST and GSP on the whole plateau were positive during 1982–2011 (Figure 3). The grassland GSNDVI increased gradually from 1982 to 2000 (Qinghai Province: slope = 0.0011 year^{-1}, $p < 0.01$, $n = 19$; Xizang Province: slope = 0.0008 year^{-1}, $p < 0.001$, $n = 19$), and then shifted to decreasing from 2000 to 2006 (Qinghai Province: slope = −0.0013 year^{-1}, $p = 0.53$, $n = 7$; Xizang Province: slope = −0.0020 year^{-1}, $p = 0.02$, $n = 7$). After
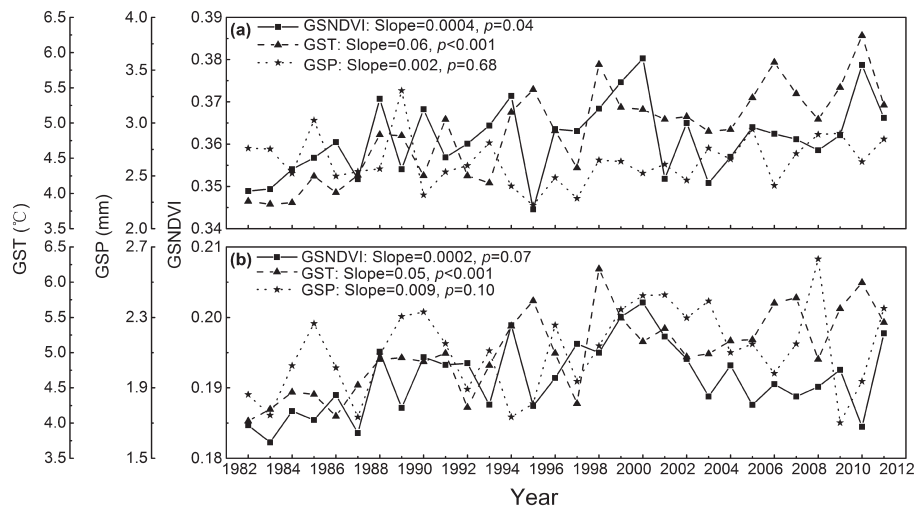
Figure 3. Interannual changes of GSNDVI, GST and GSP in Qinghai (a) and Xizang (b) Provinces from 1982 to 2011.
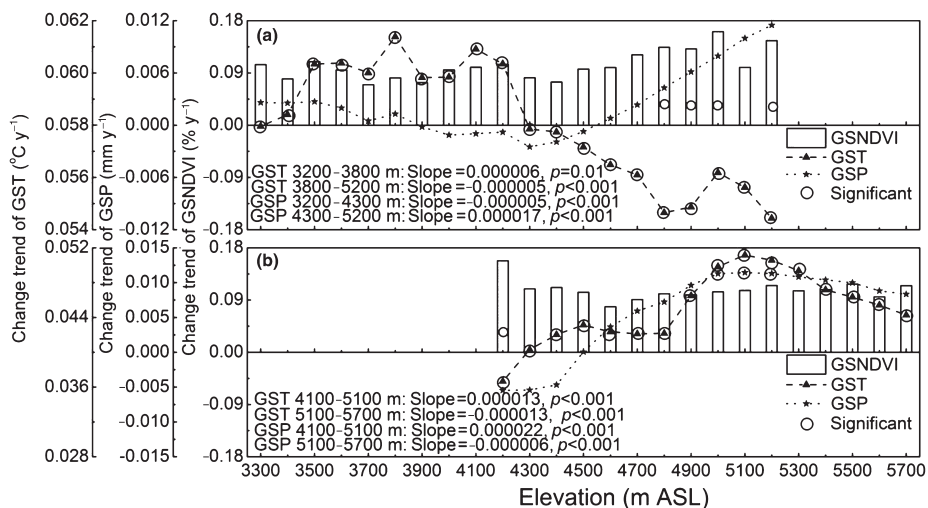

Figure 4. Change slopes of GSNDVI, GST and GSP at each elevation bin in Qinghai (a) and Xizang (b) Provinces. The white circle indicates that the change trend reached a statistically significant level ($p < 0.05$).

2006, the grassland GSNDVI followed a flat trend. During the study period, the grassland GSNDVI followed an increasing trend in the two provinces, which reached a statistically significant level in Qinghai Province. The change slopes of the grassland GST in Qinghai Province and Xizang Province were 0.06 °C year^{-1} and 0.05 °C year^{-1} with statistical significance ($p < 0.001$) during 1982–2011, respectively. No statistically significant GSP trends were observed in the two provinces.

The interannual fluctuations of the grassland GSNDVI and GSP showed different trends between Qinghai Province and Xizang Province (Figure 3). The grassland GSNDVI had larger values and increased faster in Qinghai Province (GSNDVI: 0.35–0.38, slope = 0.0004 year^{-1}) than in Xizang Province (GSNDVI: 0.18–0.20, slope = 0.0002 year^{-1}). The grassland GSP amount was also greater in Qinghai Province (GSP: 2.21–3.30 mm) than in Xizang Province (GSP: 1.70–2.63 mm). In the entire studied period, the annual GSP reversed from decreasing (1982–1995: slope = −0.02 mm year^{-1}, $p =$

0.21, $n = 14$) to increasing (1995–2011: slope = 0.03 mm year^{-1}, $p < 0.01$, $n = 17$) in Qinghai Province, but shifted from increasing (1982–2001: slope = 0.02 mm year^{-1}, $p = 0.05$, $n = 20$) to decreasing (2001–2011: slope = −0.03 mm year^{-1}, $p = 0.33$, $n = 11$) in Xizang Province.

3.2. Change trends of grassland GSNDVI, GST and GSP at different elevations

The change percentages of the grassland GSNDVI were positive at all elevation bins in Qinghai and Xizang Provinces during the past 30 years (Figure 4). Although the change percentage values fell in the same range of 0.07–0.16% year^{-1} in the two provinces, they had a greater variability among different elevation bins in Qinghai Province than in Xizang Province, especially below 4500 m ASL. In Qinghai Province, the change percentage exceeded 0.09% year^{-1} in grasslands above 4500 m ASL and reached statistically significant level above 4700 m ASL. In Xizang Province, the change percentage exceeded
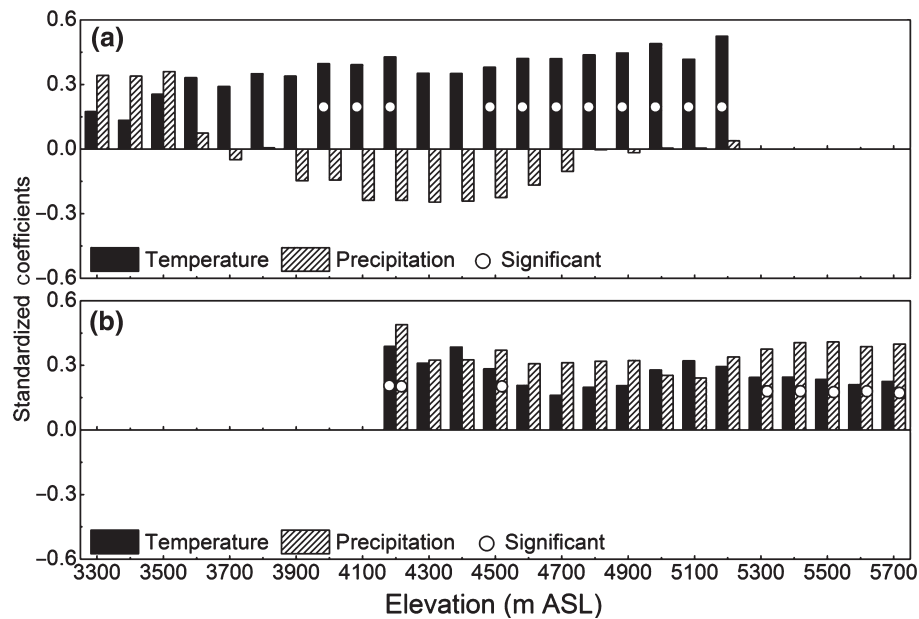
Figure 5. The standardized coefficients between GSNDVI and temperature and precipitation at each elevation bin in Qinghai (a) and Xizang (b) Provinces. The white circle dot means the correlation reached a statistically significant level ($p < 0.05$).

0.09% year^{-1} in the whole grasslands, except at the $4500-4600$ m ASL bin.

The grassland GST underwent a more drastic increase in Qinghai Province (more than $0.05\,°C$ year^{-1}) than in Xizang Province (between 0.04 and $0.05\,°C$ year^{-1}) (Figure 4). The greatest warming trends occurred in grasslands between 3400 and 4200 m ASL in Qinghai Province with a rate around $0.06\,°C$ year^{-1}. In Xizang Province, the GST warming trends were greater in grasslands above 4900 m ASL than in lower elevation grasslands. The grassland GSP showed enhanced wetting trends at higher elevations in both Qinghai and Xizang Provinces (Figure 4). The greatest wetting trends were detected above 4900 m ASL in the two provinces. The GSP wetting trends reached statistically significant levels in grasslands between 4900 and 5200 m ASL in Xizang Province. In contrast, the grassland GSP showed decreasing trends between 3800 and 4500 m ASL in Qinghai Province and below 4500 m ASL in Xizang Province, which are located in eastern Qinghai Province and southeastern Xizang Province, respectively.

3.3. Climate change in relation to elevation

The GST warming slopes changed faster in Xizang Province than in Qinghai Province along increasing elevations, though the warming slopes were larger in Qinghai Province than in Xizang Province (Figure 4). In Qinghai Province, the change trend of the warming slopes along increasing elevations shifted from increasing by $0.006\,°C$ year^{-1} per 1000 m elevation ($3300-3800$ m ASL) to decreasing by $-0.005\,°C$ year^{-1} per 1000 m elevation ($3800-5200$ m ASL). In Xizang Province, the change trend of the warming slopes along increasing elevations reversed from increasing by $0.013\,°C$ year^{-1} per 1000 m

elevation ($4100-5100$ m ASL) to decreasing by $-0.013\,°C$ year^{-1} per 1000 m elevation ($5100-5700$ m ASL).

3.4. Elevation-dependent climate sensitivities of grassland vegetation variation

The relationships between grassland GSNDVI and climate factors exhibited different patterns between Qinghai Province and Xizang Province. In Qinghai Province, the standardized regression coefficients between grassland GSNDVI and GST were positive at all elevation bins, but the standardized regression coefficients between grassland GSNDVI and GSP were negative in grasslands between 3800 and 4700 m ASL (Figure 5(a)). The absolute values of the coefficients between GSNDVI and GST were larger than those between GSNDVI and GSP in grasslands above 3500 m ASL. In particular, the coefficients between GSNDVI and GST reached statistically significant levels in grasslands above 3900 m ASL except between 4200 and 4400 m ASL. In Xizang province, the standardized regression coefficients between grassland GSNDVI and GST and GSP were positive at all elevation bins, but the standardized regression coefficients between GSNDVI and GSP were greater than those between GSNDVI and GST (Figure 5(b)). The coefficients between GSNDVI and GSP were statistically significant in grasslands above 5200 m ASL.

4. Discussion and conclusions

4.1. Interannual change of grassland GSNDVI, GST and GSP

The change trends of grassland GSNDVI identified in this study were in accordance with previous studies during 1982–2006 (Piao *et al.*, 2006b; Piao *et al.*, 2011b).

However, our finding of improved greenness under climate warming and wetting during 1982–2011 was inconsistent with previous findings of grassland degradation during 1982–2006 over the whole plateau (Piao *et al.*, 2006a; Gao *et al.*, 2010). The inconsistency could be caused by one segment of degraded greenness during 2000–2006 imbedded in the overall enhanced greenness trend during 1982–2011.

The findings of significant warming and nonsignificant precipitation trends as identified in this study across the plateau grasslands were in line with previous studies (Liu *et al.*, 2009a). The GST values were within a similar range in the two provinces, and the GSP values were larger in Qinghai Province than in Xizang Province because of a longer rainy season fed by the East Asian monsoon than by the South Asian monsoon (Molnar *et al.*, 2010), which accordingly nurtures denser grassland in Qinghai Province than in Xizang Province.

The spatial heterogeneous climate change found in the study is in accordance with prior regional-scale studies, such as faster warming in Qinghai Province than in Xizang Province (Yang *et al.*, 2011a; Zhou and Ren, 2012; Yin *et al.*, 2013), elevation-dependent wetting (Arakawa and Kitoh, 2012), and decreased GSP in the eastern and southeastern plateau (Feng and Zhou, 2012; Wang and Guo, 2012; Yang *et al.*, 2014a). The more obvious climate warming in Qinghai Province than in Xizang province could be caused by two reasons: (1) a shrunk land and atmospheric energy budget over the plateau mainly caused by enhanced outgoing longwave radiation and weaker absorbed solar radiation (Duan and Wu, 2008; Yang *et al.*, 2011b, 2014a; Wu *et al.*, 2012). (2) Snow and glacier distributed at high elevation regions can slow down climate warming by reflecting solar radiation and consuming energy due to snow/ice melting (Yang *et al.*, 2014a). The two above-mentioned effects might be more evident in Xizang Province due to a higher proportion of higher elevation region than in Qinghai province. An enhanced wetting along rising elevation might lie in that climate warming could accelerate glacier/snow thawing at high elevations, enhance local atmosphere moisture and consequently increase precipitation. Moreover, increased humidity and shrunk snow/ice would enhance income of downward long-wave radiation and absorption of solar radiation at high elevations (Rangwala *et al.*, 2010), which results in more obvious elevation-dependent climate warming in Xizang Province. The decreased GSP in the eastern and southeastern plateau was mainly caused by the weakening Asian monsoon (Xu *et al.*, 2006; Yang *et al.*, 2014a).

4.2. Change trends of grassland GSNDVI, GST and GSP at different elevations

The plateau grassland gained improved greenness, but the variability of greenness gaining among different elevations was greater in Qinghai Province than in Xizang Province. This difference could be caused by two reasons: (1) Climate regime has more evident spatial gradients in Qinghai

Province than in Xizang Province. In Qinghai Province, climates cover wider temperature and precipitation ranges, with a temperate zone in the north and a sub-arctic zone in the south for temperature, and semi-humid/humid climate in the east and semi-arid/arid climate in the west for precipitation. In Xizang province, the temperature and precipitation ranges are relatively narrower, with most grassland distributed in the sub-arctic/arctic zone with semi-arid/arid climate. (2) The anthropogenic activity disturbances are more frequent in low elevation grasslands of Qinghai Province, where the population density is higher than in Xizang Province.

4.3. Climate change in relation to elevation

Previous studies addressing an elevation-dependent climate change pattern in the plateau mainly relied on ground meteorological records of CMA meteorological stations (Liu *et al.*, 2009b; Rangwala *et al.*, 2009). These stations are mainly distributed below 4200 m ASL. In this study, we used the interpolated continuous surface results and identified steeper GST warming slopes along increasing elevations in regions below 4200 m ASL. Such finding is consistent with previous finding using ground meteorological records.

4.4. Elevation-dependent climate sensitivities of grassland vegetation

The primary climate factors causing the grassland vegetation variations were different between Qinghai Province and Xizang Province. This finding is consistent with previous studies about impacts of climate change on grassland NPP over the plateau (Piao *et al.*, 2006a; Gao *et al.*, 2009; Fan *et al.*, 2010; Piao *et al.*, 2012). In Qinghai Province, temperature played a more important role in driving grassland growth than precipitation. In contrast, precipitation contributed a higher proportion than temperature in Xizang Province. This drastic contrast could be due to different climate sensitivity of grasslands between the two provinces. Different thermal heating systems and disparate water vapour sources form distinct climates between the two provinces (Yanai and Li, 1994; Yang *et al.*, 2006, 2007a; Liu *et al.*, 2008; Molnar *et al.*, 2010). The different terrain and topography features further intensifies the climate differences between the two provinces (Chen *et al.*, 2012; Wang and Guo, 2012; Yang *et al.*, 2014a), which results in different grassland vegetation zones and a divergent climate sensitivity between the two provinces (Chang, 1983; Smith and Shi, 1992). This finding further implied the important role of geographic topography in driving local climate and ecosystem process, which also has been identified in Inner Mongolia Plateau in China (Dong *et al.*, 2011).

The greater climate sensitivity of alpine grassland at higher elevations is related to the elevation-dependent gradients of ecosystem properties, such as plant element composition, species structure and soil microbial communities. At higher elevations, the alpine grassland can enrich foliar nitrogen element to strengthen photosynthetic

capacity (Zhou *et al.*, 2011; Zhou *et al.*, 2013b; Zhou *et al.*, 2013a). Along rising elevations, species diversity decreases and the proportion of endemic species increases (Vetaas and Grytnes, 2002; Wang *et al.*, 2003; Klein *et al.*, 2004; Li *et al.*, 2014). At higher elevations, soil microbial communities can aggregate cold shock, nitrogen cycling and sulfur cycling genes to adapt cold environment (Fu *et al.*, 2012; Yang *et al.*, 2013, 2014b), which set the stage for an enhanced capacity to cope with harsh environment for the higher elevation grasslands than the lower elevation grasslands. Furthermore, the elevation-dependent climate warming and wetting provide a more favourable condition for the plateau grassland at higher elevations, and the grassland consequently gained enhanced improvement along increasing elevations. On the other hand, the ever-increasing anthropogenic activities are playing an increasing role in driving vegetation variation in low elevation grasslands, which can confound our understanding on vegetation response to climate (Yu *et al.*, 2012).

Previous related studies regarding the plateau vegetation response to climate change have been mostly based on time series datasets that were shorter than 30 years. This study employed a full 30-year climate and NDVI series data. To our knowledge, in the meantime, this study is the first by separating the plateau into two units (as separated by Tanggula Mountains) in evaluating vegetation's elevation-dependent sensitivities to climate change in the Qinghai-Xizang Plateau. The entire plateau grasslands experienced a significant warming in growing season during 1982–2011. However, the grassland vegetation features different climate sensitivities between the two geographic units, with temperature and precipitation being the main driving factor in Qinghai Province and Xizang Province, respectively. In particular, the high elevation grasslands in the plateau were characterized with higher climate sensitivity.

It should be pointed out that our results could still largely be affected by the qualities of the remote sensing data and the climate data interpolation method. The earlier version of the GIMMS NDVI dataset (i.e. 1982–2006) has been compared to differ from SPOT and MODIS NDVIs during 2001–2006 and can be biased in the western plateau (Dong *et al.*, 2013; Zhang *et al.*, 2013). Site-specific analysis based on field observations could further improve our understanding on the complicated relationship between climate change and alpine grassland variations in the future. Furthermore, our baseline map that defined grassland distribution was based on the land-cover data in 2000. It is highly likely that some grassland pixels might have changed into other land-cover types during our study period.

Acknowledgements

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