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Temporal and Spatial Variations in the Climate Controls of Vegetation Dynamics on the Tibetan Plateau during 1982–2011

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ABSTRACT

The ecosystem of the Tibetan Plateau is highly susceptible to climate change. Currently, there is little discussion on the temporal changes in the link between climatic factors and vegetation dynamics in this region under the changing climate. By employing Normalized Difference Vegetation Index data, the Climatic Research Unit temperature and precipitation data, and the in-situ meteorological observations, we report the temporal and spatial variations in the relationships between the vegetation dynamics and climatic factors on the Plateau over the past three decades. The results show that from the early 1980s to the mid-1990s, vegetation dynamics in the central and southeastern part of the Plateau appears to show a closer relationship with precipitation prior to the growing season than that of temperature. From the mid-1990s, the temperature rise seems to be the key climatic factor correlating vegetation growth in this region. The effects of increasing temperature on vegetation are spatially variable across the Plateau: it has negative impacts on vegetation activity in the southwestern and northeastern part of the Plateau, and positive impacts in the central and southeastern Plateau. In the context of global warming, the changing climate condition (increasing precipitation and significant rising temperature) might be the potential contributor to the shift in the climatic controls on vegetation dynamics in the central and southeastern Plateau.

Key words: vegetation dynamics, climate control, temporal and spatial variations, Tibetan Plateau

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1. Introduction

The Tibetan Plateau, often referred to as “the third pole of the Earth”, covers nearly a quarter of the total land area of China [Fig. S1 in Electronic Supplementary Material (ESM)], with an average altitude of over 4000 MSL. Due to its unique orographic and topographic features, the Plateau not only plays an important role in global climate regimes, especially for the Asian monsoon system through dynamic (Ye and Gao, 1979) and thermal mechanisms (Hsu and Liu, 2003; Zhang et al., 2004), but also is crucial for the terrestrial carbon cycle (Cheng and Wu, 2007; Babel et al., 2014), which has experienced a carbon loss in recent years as a result of permafrost collapse (Mu et al., 2016; Wu et al., 2016) and grassland degradation (Li et al., 2013). Moreover, the Tibetan Plateau

is also the source region of several great rivers of Asia and is known as Asia’s “Water Tower” (Xu et al., 2008; Immerzeel et al., 2010; Yao et al., 2012). Consequently, ecological and environmental changes on the Plateau may exert substantial influences on the livelihoods of the billions of people living in the region. Therefore, studies on ecosystem evolution in this region and its responses to climatic factors are of great importance from both scientific and societal points of view.

The Tibetan Plateau is one of the most vulnerable areas to climate change (e.g., Cui and Graf, 2009; Wang et al., 2011; Chen et al., 2013). A number of recent studies have been published on the influence of climate change in vegetation dynamics as well as phenology over the Plateau (e.g., Gao et al., 2013; Che et al., 2014; Shen et al., 2015a), based on evidence from the NDVI (e.g., Pang et al., 2017) as well as tree-ring data (Yang et al., 2017), but the nature of the change in the trend remains a matter of debate. For instance, several studies have found a turning point for the vegetation dynamics of

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the Tibetan Plateau over the past three decades based on the Global Inventory Modeling and Mapping Studies (GIMMS) NDVI (e.g., Piao et al., 2011a; Chen et al., 2014b), while others report an increasing trend in vegetation growth in the northeastern Plateau throughout 1982–2011 when utilizing other NDVI data sources (e.g., Shen et al., 2015b). Likewise, there is also controversy regarding the vegetation phenology of the Plateau. For instance, Yu et al. (2010) reported a delayed spring phenology after short-term advances as a result of sustained wintertime warming, with limiting fulfillment of chilling requirements and other factors (e.g., Chen et al., 2011; Yi and Zhao, 2011). However, Zhang et al. (2013a) doubted the data quality of GIMMS NDVI in most parts of the western Plateau and insisted that the start date of plant phenology has continuously advanced with a lengthened growing season, but there is still some debate around this view (e.g., Shen et al., 2013; Wang et al., 2013). Despite these disputes, one certainty is that the Tibetan Plateau has experienced substantial changes in vegetation growth over recent decades.

The ecosystem of the Tibetan Plateau is highly susceptible to climate change, and through various feedback processes between the atmosphere and biosphere (Gu et al., 2005; Kato et al., 2006) its evolution plays a crucial role in regional (Li and Xue, 2010; Shen et al., 2015b) and global (Wu et al., 2007) climate change. Recent studies have indicated that climate change, particularly variations in temperature and precipitation, affect vegetation dynamics (e.g., Liu et al., 2013; Otto et al., 2016). For the majority of the Tibetan Plateau, Zhou et al. (2007) suggested that vegetation activity is controlled mainly by temperature (thermal) variations, with positive correlations between temperature and vegetation dynamics in alpine ecosystems (Piao et al., 2011a), whereas precipitation plays a relatively minor role. Nevertheless, as global warming progresses, the influences of precipitation (Gao et al., 2009; Shen et al., 2011) and temperature (Yu et al., 2010; Zhang et al., 2013b) on vegetation dynamics on the Plateau remain a matter of debate.

Temporal and spatial variations in the relationship between vegetation dynamics and climatic factors have been reported in other regions. For instance, Buermann et al. (2014) reported that, from the mid-1990s onward, the initially positive correlation between summer temperature and NDVI in boreal forest zones became negative, possibly due to the warming-induced drought stress. However, on the Tibetan Plateau, although many recent studies (e.g., Ding et al., 2007; Zhong et al., 2010; Zhang et al., 2013b; Hua et al., 2015) have reported spatial differences in correlations between climatic factors and vegetation dynamics, it remains unclear whether a temporal switch has occurred in the relationship between vegetation dynamics and climate change. Such a switch could lead to profound shifts in the ecosystem and, consequently, the response of the regional and global climate system. To this end, the objective of this study is to investigate the variations in the associations between the vegetation dynamics and climate change over the Tibetan Plateau over the last few decades.

2. Materials and methods

The GIMMS NDVI dataset (specifically: NDVI-3g), derived from the AVHRR sensor (Pinzon and Tucker, 2014) and corrected for calibration, view geometry, volcanic aerosols, and other factors unrelated to vegetation change (Tucker et al., 2005), was employed as an index of vegetation dynamics (Chen et al., 2014a), with spatial and temporal resolutions of $(1/12^\circ) \times (1/12^\circ)$ and 15 days, respectively. By employing the Maximum Value Compositing technique (Holben, 1986), the highest NDVI value from each 15-day period was extracted and combined into the growing season NDVI series (Goward et al., 1985). Pixels with sparse vegetation (mean NDVI < 0.1) were excluded, as suggested previously (Piao et al., 2011b), which resulted in nearly 25% of the Plateau area being excluded in this study.

A monthly precipitation and temperature gridded dataset ($0.5^\circ \times 0.5^\circ$ spatial resolution) from 1982 to 2011 was acquired from the University of East Anglia (the CRU's TS 3.21 dataset: <http://www.cru.uea.ac.uk/cru/data/>) (Mitchell and Jones, 2005). Due to the large gap in grid size between the NDVI and CRU datasets, Pearson's correlation coefficient was calculated between each NDVI grid point and the nearest CRU grid point during the growing season (the mean of May to September). We calculated the Pearson's correlation coefficients between the vegetation dynamics (i.e., NDVI time series of the current growing season) and growing season precipitation (both the previous and the current year) (Herrmann et al., 2005), as well as temperature (current growing season). In addition, monthly in-situ meteorological records (Fig. S1 in Electronic Supplementary Material) as well as MODIS NDVI were also employed to verify the correlation results between the gridded CRU and NDVI datasets.

To explore the relationship between climate change and vegetation dynamics at the interannual time scale (Buermann et al., 2014), linear trends were removed before the Pearson's correlations were calculated (see Electronic Supplementary Material). Since there is a significant ($p < 0.05$) difference in the trends in the areal mean NDVI series before and after 1996 (Fig. S2), Pearson's correlation coefficients were calculated for the sub-periods of 1982–96 and 1997–2011. As the correlation coefficients of the two sub-periods had the same degrees of freedom (DF = 13), we evaluated the difference in the coefficients between the two sub-periods to highlight changes in the correlation. In order to determine the relative role of temperature and precipitation, partial correlations were also used to illustrate the temporal changes in the climate controls on vegetation dynamics over the Plateau. A nine-year moving-window correlation between NDVI and the precipitation/temperature series was also performed. In addition, in order to better identify the spatial variations in the correlation between climate drivers and vegetation growth, the Tibetan Plateau has been divided into 11 physico-geographical areas (Zheng, 1996) (Fig. 1), as suggested previously (e.g., Ding et al., 2007; Hua et al., 2015).

where needle-leaf forest and shrubland are distributed, the most moisture resource for trees comes from deep soil water (Hua et al., 2015), and thus it takes a certain period of time for the vegetation dynamics to respond to precipitation changes (Bigler et al., 2007). Moreover, the finer-grained soil of the southeastern Plateau (Brady and Weil, 1999) with a higher water holding capacity may also be the contributor for the significant correlation between NDVI and precipitation accumulated during a longer time period (Lloret et al., 2007).

3.2. Relationship between temperature and vegetation dynamics

From the early 1980s to the mid-1990s, there was no significant correlation ($p > 0.10$) between variations in temperature and growing season NDVI for most of the Plateau, despite some scattered areas (e.g., the IIC1, IC1, and IIC2 zones) with significant negative correlations (Fig. 3a). From the mid-1990s, significant correlations ($p < 0.05$) between temperature and growing season NDVI were obtained in the IC1, IB1, and IIAB1 zones (i.e., the central and southeastern part of the Plateau) (Fig. 3b), although negative correlations were recorded in the IC2, IIC1, and IIC2 zones. The difference in the correlation coefficients pre- and post-1996 (Fig. 3c) shows a strengthening relationship between temperature and growing season NDVI in the central and southeastern part of the Plateau, suggesting the key factor controlling vegetation dynamics in these regions switched from precipitation to temperature during the mid-1990s.

The effects of rising temperature on vegetation dynamics were spatially variable across the Tibetan Plateau. A negative relationship between NDVI and temperature, as seen in the IC2, IIC1, and IIC2 zones (i.e., the southwestern and north-eastern Plateau) after the mid-1990s, suggests that rising temperature (Wang et al., 2008) leads to warming-induced moisture deficits (Beck et al., 2011), thereby suppressing vegetation activity (Zhao and Running, 2010). In these regions with relative low annual mean precipitation (< 400 mm), the suppressing effect of temperature-rise-driven moisture deficits on vegetation dynamics after the mid-1990s was also illustrated by the significant positive correlations between growing season NDVI and the Palmer Drought Severity Index (PDSI) series (See Electronic Supplementary Materials and Fig. S3), which suggests moisture is a key limiting climatic factor for vegetation activity. Therefore, in these regions the temperature increase had a negative impact on vegetation activity after the mid-1990s.

By comparison, in the central and southeastern Plateau (e.g., the IC1, IB1, and IIAB1 zones), after the mid-1990s temperature variations were significantly and positively correlated with NDVI. In these areas, due to high amounts of annual precipitation (> 400 mm), moisture was not the dominant control on vegetation growth, as indicated by the insignificant relationship between PDSI and NDVI (Fig. S3). As a result, rising temperature did not increase drought stress, but did lengthen the growing season (Liu et al., 2006) and enhance vegetation activity (Nemani et al., 2003). Therefore, after the mid-1990s, temperature rise played a positive role

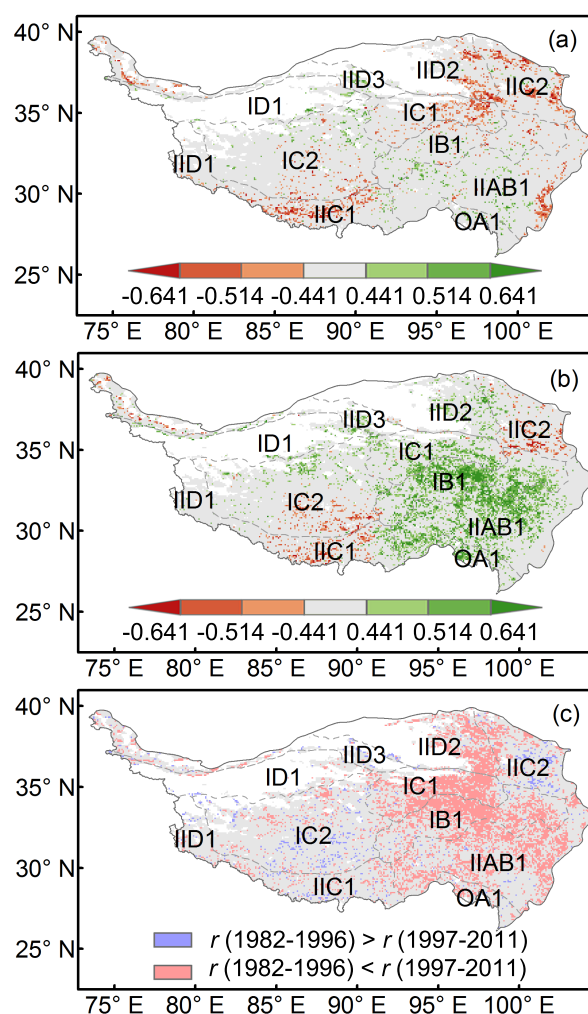


Fig. 3. Pearson's correlation coefficient between the detrended growing season NDVI and temperature on the Tibetan Plateau for (a) 1982–96 and (b) 1997–2011 [areas with non-significant ($p > 0.1$) correlation coefficients are shown in grey], and (c) the difference between the coefficients before and after 1996 (only areas with a differences of > 0.45 are shown).

on vegetation activity of the central and southeastern Plateau.

In addition, results from MODIS NDVI also showed that, during the period of 2000 to 2011, vegetation activity in the central and southeastern part of the Plateau had closer relationships with temperature than that of precipitation of both the previous and concurrent growing season (Fig. S4), and the correlation coefficients of the areal mean time series were 0.663 ($p < 0.05$) and -0.225 ($p = 0.460$) for temperature and precipitation of the previous year, respectively, all of which further support our finding regarding climate control changes from the mid-1990s onward.

3.3. Temporal trends in the factors controlling vegetation dynamics in the central and southeastern Plateau

The ecosystem of the central and southeastern part of the Plateau is of greater importance to regional and global climatic and environmental changes than other regions on the

Plateau (Immerzeel et al., 2010). Over the past three decades the central and southeastern Plateau has experienced changes in the main climate controls on vegetation dynamics. Correlation analyses of the areal mean NDVI series (e.g., the IC1, IB1, and IIAB1 zones) with mean CRU precipitation of the previous year demonstrate a change from a positive and significant correlation ($r = 0.54$, $p = 0.04$) during the early 1980s to the mid-1990s to a negative and non-significant correlation of -0.01 ($p = 0.96$) during the mid-1990s to the early 2010s. The nine-year moving correlation coefficient between the areal mean precipitation and NDVI also reveals that the importance of precipitation as a control on vegetation dynamics gradually decreased from the early 1980s to the present, as indicated by the decrease in the correlation coefficient from ~ 0.70 ($p < 0.05$) before the mid-1990s to -0.30 ($p > 0.30$) by the early 2010s (Fig. 4a). These results indicate that, as temperature increases, precipitation plays a weakening role in the vegetation dynamics over the central and southeastern part of the Plateau.

After the mid-1990s, the importance of temperature as a controlling factor on vegetation dynamics increased in the central and southeastern part of the Plateau. For instance, from the early 1980s to the mid-1990s, the correlation coefficient between areal mean NDVI and temperature was only 0.04 ($p = 0.89$), compared with 0.58 ($p = 0.02$) from the mid-1990s to the early 2010s. The nine-year moving correlation results also show that before the mid-1990s the temperature

was negatively and non-significantly correlated with vegetation activity (r is around -0.10 , $p > 0.70$), whereas from the mid-1990s the correlation coefficient increased to near 0.50 ($p < 0.20$) and even to over 0.60 ($p < 0.10$) in the late 2000s (Fig. 4b). This result suggests that, with the occurrence of global warming, temperature is an increasingly important control on vegetation dynamics. The results with in-situ data also display a similar pattern to that of the gridded dataset and the shift in the correlation with climate factors (Fig. S5).

On the other hand, the significant negative ($r = -0.416$, $p = 0.025$) autocorrelation of the growing season precipitation time series (i.e., the correlation between precipitation of the previous and of the current year) and the relationship between precipitation and temperature may affect the correlation between climate factors (i.e., temperature/precipitation of the previous year) and NDVI. Therefore, a partial correlation was performed to remove the influence of these connections on the correlation between each climate factor and vegetation dynamics. The result shows that when their relationship with precipitation of the current year was excluded, the correlation of neither the temperature or the precipitation in the previous year with NDVI was weakened obviously (Table 1). During the period of 1982 to 1996, the partial correlation of precipitation in the previous year decreases to 0.661 to 0.582 , but they are both significant ($p < 0.05$); whereas, from 1997 to 2011, the partial correlation coefficient of temperature increases slightly, from $p = 0.557$ to $p = 0.595$, both of

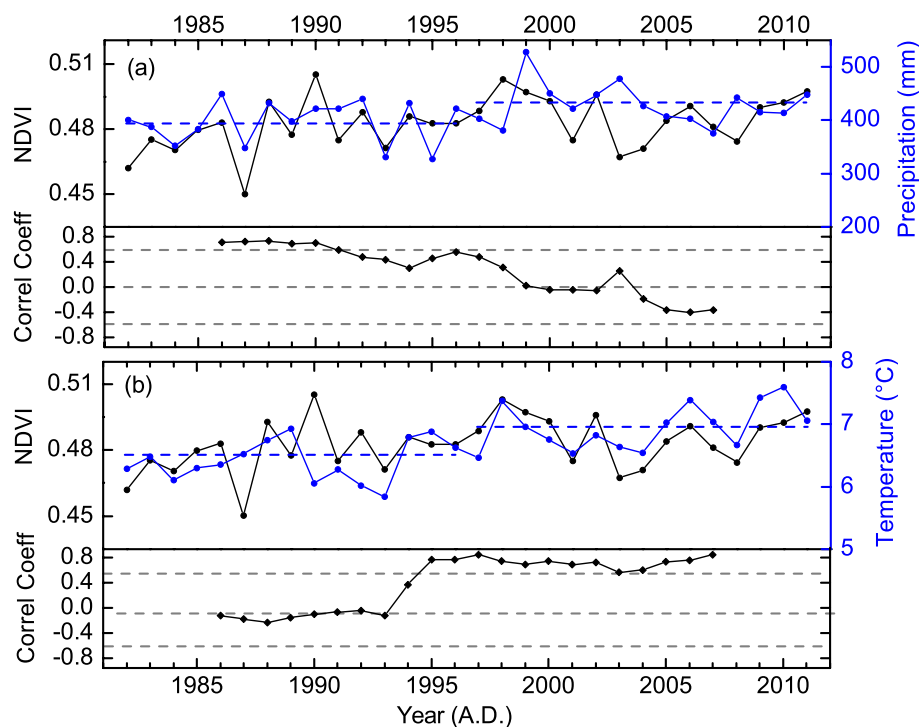


Fig. 4. Temporal trends in growing season vegetation activity (1982–2011) and its correlations with the gridded (a) precipitation in the previous year and (b) temperature on the central and southeastern Tibetan Plateau. Correlation coefficients were calculated using a nine-year moving window with trends pre-removed. Correlation coefficients above/below the horizontal gray dashed lines are statistically significant ($|r| > 0.582$; $P < 0.1$).

Table 1. Partial correlation coefficients and their corresponding significance levels (in parentheses) between each climate factor and the NDVI series during the growing season in the central and southeastern Tibetan Plateau (i.e., IC1, IB1, IIAB1) in the periods 1982–1996 and 1997–2011. The linear trends of all series were pre-removed.

Controlling factor	1982–1996			1997–2011		
	Pre_previous	Pre_current	Tmp	Pre_previous	Pre_current	Tmp
None	0.661 (0.010)	−0.396 (0.143)	−0.098 (0.792)	−0.122 (0.664)	−0.163 (0.561)	0.557 (0.031)
Pre_previous	–	0.108 (0.726)	−0.198 (0.517)	–	−0.170 (0.562)	0.554 (0.040)
Pre_current	0.582 (0.037)	–	−0.212 (0.466)	−0.131 (0.656)	–	0.595 (0.025)
Tmp	0.673 (0.012)	−0.433 (0.122)	–	0.103 (0.727)	−0.297 (0.303)	–

Note: “Pre_previous”, “Pre_current” and “Tmp” are abbreviations for the growing season precipitation in the previous year, the growing season precipitation in the current/same year, and the growing season temperature, respectively.

which are significant at the 0.05 level.

In addition, the spatial pattern in the partial correlations of vegetation activity with temperature and precipitation of the previous year were also analyzed in both sub-periods. Following the method of a previous study (Wu et al., 2015), the absolute value of the partial correlation coefficients (0–1) was linearly scaled to 0–255, and the scaled values of temperature and precipitation were then performed on red and green in the RGB (Red, Green, and Blue) color mode, respectively (the other primary color is constant), which illustrates the relative role of temperature and precipitation in the vegetation activity. The result shows that, before 1996, the vegetation activity in most of the central and southeastern Plateau was mainly controlled by precipitation variations (Fig. 5a), while after 1997 it was driven primarily by temperature changes (Fig. 5b). These different patterns also suggest a shift in the main climate controls on vegetation from precipitation to temperature.

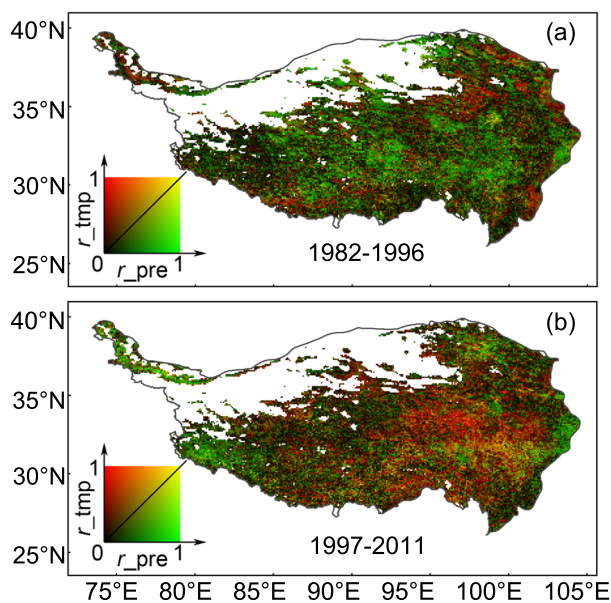


Fig. 5. Partial correlation coefficients between the detrended growing season NDVI and precipitation in the previous year on the Tibetan Plateau for (a) 1982–96 and (b) 1997–2011.

3.4. Possible mechanism for the temporal variations in the controls on vegetation dynamics

With the development of global warming, the central and southeastern Plateau has also been experiencing climate change in recent decades (Figs. S6 and S7). As suggested by Piao et al. (2006), the relationship between climatic factors and vegetation dynamics is closely linked with the climate condition and will vary with the changing climate system, which might be the reason for the temporal variations in the climate controls of vegetation growth in the central and southeastern Plateau.

To verify this assumption, we also analyzed the relationships between the correlation coefficient of each meteorological station (between climate time series and NDVI) and their corresponding mean temperature and precipitation during the two sub-periods, respectively (Fig. 6). It is clear that the correlation coefficient between NDVI and precipitation during 1982–1996 is higher than that of 1997–2011, while the correlation coefficient of temperature is higher during 1997–2011, which are both consistent with the statements mentioned above. The correlation between NDVI and precipitation in the previous year is more dependent on the mean precipitation than the mean temperature (Figs. 6a and b), and there were significant ($p < 0.10$) and negative relationships between them for both sub-periods, which indicates that increasing precipitation may cause a declining connection between NDVI and precipitation in the previous year. However, the correlation coefficient between NDVI and temperature is more linked with temperature (Figs. 6c and d), and their positive relationships show that higher temperature appears to be associated with a closer correlation between temperature and vegetation growth.

In the central and southeastern part of the Plateau, the relationships between precipitation in the previous year and NDVI decreases as the mean precipitation increases, while the favorable influence of temperature on vegetation growth tends to increase as the mean temperature rises. As global warming progresses, the increasing (albeit non-significant) precipitation, and the significant rising temperature, in the central and southeastern Plateau (Figs. S6 and S7) might contribute to the weakening influence of precipitation and the strengthening influence of temperature on vegetation activ-

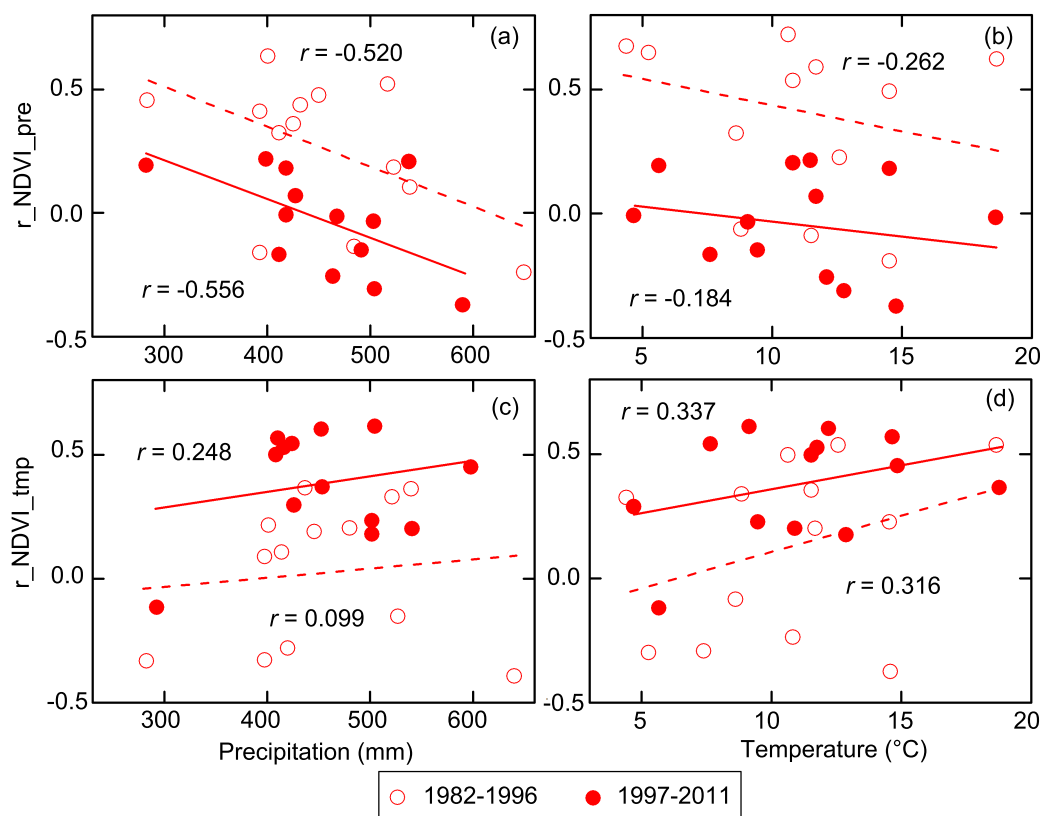


Fig. 6. Variations in the correlation coefficient (r) between the detrended growing season NDVI and the in-situ precipitation of the previous year/temperature along with their corresponding mean (a)/(c) precipitation and (b)/(d) temperature over the central and southeastern Plateau from 1982 to 1996 (open circles) and from 1997 to 2011 (solid circles). The solid (dashed) lines are the linear regressions (also shown by correlation coefficients r) between correlations and precipitation of previous year/temperature obtained from the least-squares method.

ity, respectively. Therefore, the shift in the controlling factor on regional vegetation dynamics can be regarded as the result of their responses to the changing climate condition under global warming.

4. Conclusions

In the central and southeastern Tibetan Plateau, the dominant climatic control on vegetation dynamics has switched from precipitation to temperature over the past few decades, possibly due to the changing climate condition in the context of global warming. Contrary to previous work showing climate-warming-induced drought stress to vegetation growth for several other regions (e.g., Buermann et al., 2014), our study—with a focus on the ecosystem of the Plateau area—provides evidence that a positive response has become pervasive since the mid-1990s. In addition to the lengthened growing season, another potential contributor for the positive impact on vegetation dynamics of Plateau areas might be the increasing water use efficiency, which enables resilience to warming-induced moisture stress as a result of decreased stomatal density and conductance of water driven by increasing CO_2 concentrations (Keenan et al., 2013). However, due

to the shortness of observations and limited station coverage, this finding needs to be taken with some caution. Moreover, the mechanism that underlies such switches since the mid-1990s remains unclear, which should be addressed in future studies.

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