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

Ting HUA\textsuperscript{1,2,3} and Xunming WANG\textsuperscript{4}\textsuperscript{,1}

\textsuperscript{1}Key Laboratory of Desert and Desertification, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China
\textsuperscript{2}Shaanxi Key Laboratory of Earth Surface System and Environmental Carrying Capacity, College of Urban and Environmental Science, Northwest University, Xi’an 710172, China
\textsuperscript{3}Institute of Coastal Research, Helmholtz-Zentrum Geesthacht, Geesthacht 21502, Germany
\textsuperscript{4}Key Laboratory of Water Cycle \& Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

(Received 5 January 2018; revised 21 March 2018; accepted 17 April 2018)

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


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...
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, affects 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 $(1/12') \times (1/12')$ 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 $(0.5' \times 0.5'$ 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).