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Research Paper

Vegetation phenology on the Qinghai-Tibetan Plateau and its response to climate change (1982–2013)

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A B S T R A C T

Using NDVI3g vegetation index, we defined 18 phenology metrics to investigate phenological change on the Tibetan Plateau (TP). Considering the heterogeneity of vegetation phenology, we divided TP into 8 vegetation clusters according to a 1:1000000 vegetation cluster map. For regions where phenology is highly sensitive to climate, we investigated the impact of climate variables, such as temperature, precipitation, and solar radiation on phenology using the partial least squares regression (PLS) method. Results indicated (1) that turning points of the starting date of the growing season (SOS) metrics were in 1997–2000, before which SOS metrics advanced 2–3d/10a. The ending date of the growing season (EOS) and the length of growing season metrics (LOS) turning points were 2005 and 2004–2007, respectively. Before the turning points, the EOS metrics had a delayed tendency of 1–2d/10a, and the LOS metrics also had a prolonging tendency of 1–2d/10a. After the turning points, the significant levels of SOS and EOS metrics' tendency only reached 0.1, and LOS's tendency was insignificant at the 0.1 level. (2) Alpine meadows and alpine shrub meadows changed most intensely on TP. Advanced SOS and delayed EOS were the main reasons of the alpine meadow LOS extension. Advance SOS mainly contributed to the alpine shrub meadow LOS extension. (3) We used meteorological variables, such as temperature, precipitation and solar radiation, to analyze the drastic change of the phenology of alpine meadows and alpine shrub meadows through the PLS method. Temperature was found to be the dominant meteorological variable impacting phenology. In those regions, the previous year autumn and early winter temperature had a positive effect on the SOS phenology. The high temperature in this period would postpone previous year EOS, indirectly delaying SOS in the current year. On the other hand, warming autumn and early winter may slow the fulfilment of chilling requirements and lead to later SOS, which would have a delayed effect on SOS. Except summer, the minimum temperature had a similar effect on vegetation phenology, as average and maximum temperature. Furthermore, the effect of precipitation on phenology fluctuated widely across different months. The previous year autumn and winter precipitation had a negative effect on the SOS phenology, and early spring precipitation had a positive effect. The main factor limiting vegetation development in August was precipitation, and during this month precipitation had a positive impact on the EOS phenology. The influence of solar radiation was mainly during summer and early fall. This study will contribute toward vegetation phenology model improvement.

1. Introduction

Phenology, studying the timing of recurring biological cycles and their relation to climate change, provides an independent measure of how ecosystems are responding to climate change (Linderholm, 2006; Parmesan, 2006; White et al., 2009). It is now acknowledged that climate change remarkably impacts terrestrial ecosystems (Walther et al., 2002; Kelly and Goulden, 2008; Reichstein et al., 2013; Zhou et al., 2014; Wu et al., 2015). Meanwhile, as an important component of the Earth system vegetation modulates regional and global climate change by biogeochemical and biophysical feedbacks (Field et al., 2007; Peñuelas et al., 2009; Tan et al., 2015). Therefore, monitoring

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vegetation phenology is critical for understanding the vegetation response to a changing climate as well as for enumerating the feedback mechanisms that vegetation response may generate for the climate itself (Cleland et al., 2007; Morisette et al., 2009; Peñuelas et al., 2009; Garonna et al., 2016). Hence, decadal trends and interannual variability of vegetation phenology merits analysis, because they can shed light on the modification of carbon (e.g. Jeong et al., 2012), and water and energy exchange (Obrist et al., 2003) between vegetation and atmosphere (White et al., 2009). Hence, monitoring land surface phenology (LSP) is important for elucidating the land-atmosphere-energy exchange (Shen et al., 2016) and its representation in terrestrial biosphere models (Garonna et al., 2016).

The Qinghai-Tibetan Plateau (QTP), also known as the 'Earth's third pole', is the highest and largest plateau of the globe, covering approximately 2.5 million km^2 at an average elevation of 4000 m (e.g. Chen et al., 2015). The QTP has a unique vegetation composition and climate properties along with low degree of human interference (e.g. Piao et al., 2011). It has unique climate features, such as intense solar radiation, longer sunshine duration, lower air temperature and pressure, less cloud cover, and discernable seasonal and spatial inhomogeneity of precipitation. These features make the QTP the principle regional driver and amplifier of global climate change (Liu and Chen, 2000; Dong et al., 2012; Che et al., 2014). Numerous studies have shown that vegetation in this region is highly sensitive to climate change (Shen et al., 2011; Dong et al., 2012; Zhang et al., 2013a,b; Che et al., 2014). However, observed climate records of the past three decades show a very substantial climate change on the QTP (Liu and Chen, 2000) which has been characterized by significant warming with a temperature rise of about 0.4 °C per decade (Dong et al., 2012; Wang et al., 2012; Shen et al., 2014). This warming rate is believed to be higher than that for the northern and southern hemispheres as well as for the globe as a whole (Trenberth et al., 2007). Besides, previous studies have pointed out that terrestrial ecosystems on the QTP acted as a small carbon sink (e.g. Zhang et al., 2009; Piao et al., 2011). Hence, climate change and its impact on vegetation phenology on the QTP is a matter of global concern.

Numerous studies have addressed the effect of warming climate on vegetation phenology (e.g. Shen et al., 2014), such as increasing vegetation productivity (Wang et al., 2012; Xu et al., 2011), higher ecosystem respiration (Lin et al., 2011; Tan et al., 2010), loss of species diversity (Klein et al., 2004; Wang et al., 2012), advancing spring phenology (Zhang et al., 2013a,b), glacier retreat (Yao et al., 2012), and thawing of permafrost (Wu et al., 2013). Several of these studies have focused on vegetation growing season, and starting and ending dates of spring and autumn vegetation phenology. However, results of these studies are always not in agreement. Dong et al. (2012) suggested that the regional average growing season length had a significant increasing trend with an increasing rate of 3.29 days/decade, and this change was attributed to an earlier start of the growing season (−1.82 days/decade). They also argued that the variation in the growing season indices throughout the TP during the last 50 years was strongly correlated with elevation. However, Yu et al. (2010) indicated that during 1982–2006 for meadow and steppe vegetation on the QTP, spring phenology initially advanced, followed by retreating in the mid-1990s in spite of continued warming. Together with the advancing end of the growing season for steppe vegetation, this led to a shortening of the growing period. Nevertheless, relations between vegetation growing season and altitude were identified by Ding et al. (2012) and Dong et al. (2012). Chen et al. (2015) reported no continuous advancing trends of green-up dates during 1982–2011, and no turning points in the mid to late 1990s. Therefore, chilling requirements were not suggested as an important driver influencing the green-up response to spring warming (Chen et al., 2015).

The above-mentioned discrepancies in research results and/or scientific viewpoints call for further analysis based on updated long term observed vegetation data and full consideration of potential drivers. The significance of the current study can be justified, because strong environmental gradients can be expected due to the unique geographical conditions of the QTP (Qin et al., 2009; Shen et al., 2014), which result in spatial heterogeneity of water and temperature conditions, causing diverse phenological responses to warming across the plateau (Shen et al., 2011). Besides, discrepancies in relations between vegetation growing season, spring and/or autumn vegetation phenology, are because vegetation growth or green-up activities should be attributed to more than one driver such as precipitation and temperature. For example, numerous studies have found that precipitation and sunshine duration in the plateau were the major factors for vegetation growth (e.g. Mao et al., 2007; Che et al., 2014). It is therefore necessary to further analyze spatiotemporal variations of vegetation phenology and their relation with climatic factors across the QTP.

Focusing on discrepancies in vegetation phenology and related causes in the QTP, this study investigated the entire vegetation phenology changes via definitions of 18 vegetation phenological metrics. Considering the spatial heterogeneity of water and temperature conditions and related different vegetation responses, this study classified the entire QTP into different vegetation regions and then analyzed vegetation phenology changes for each individual vegetation region. The partial least squares regression model (PLS) was used to analyze the lagging effect of vegetation response to climate change with the aim to differentiate time intervals when climate variables have different influences on vegetation phenology. The objectives of this study therefore are to address: (1) changes in the vegetation phenology on the QTP, and (2) the climate variables that have specific impacts on vegetation phenology across different vegetation regions on the QTP. For accomplishing these objectives, this study defined 18 vegetation phenological metrics, based on NDVI3g data, and the entire QTP was categorized into 8 vegetation regions, based on a vegetation map of scale of 1:1000000. Potential impacts of climatic variables, such as maximum/minimum air temperature, average air temperature, precipitation, and solar radiation on vegetation phenology were analyzed using the PLS model. This study can provide a full picture of vegetation phenology during the period of 1982–2013 and related climatic drivers across the QTP.

2. Data

2.1. Normalized difference vegetation index (NDVI)

NDVI is a vegetation indicator that has been widely used for quantifying vegetation biomass (Kong et al., 2017), growing processes, and phenology. The NDVI dataset analyzed for phenological metrics is the 3rd-genetation NDVI by Advanced Very High Resolution Radiometer (AVHRR) instrument from the NOAA satellite series 7, 9, 11, 14, 16, and 17, with spatial resolution of 1/12° and biweekly time step, and covered a period of July 1981–December 2013 (https://ecocast.arc.nasa.gov/data/pub/gimms/3g.v0). This dataset has been corrected by calibration, view geometry, volcanic aerosols, and other effects that have no relation with vegetation change (Pinzon and Tucker, 2014). The NDVI dataset covering the completed year during 1982–2013 was used in this study. Due to the spatial heterogeneity of vegetation phenology, TP was subdivided into 9 clusters based on a 1:1000000 vegetation cluster map (Fig. 1), wherein tropical rainforest was removed because of its less than obvious NDVI seasonal change. Thus, altogether 8 clusters were included.

2.2. Meteorological data

Average temperature (Tavg), maximum temperature (Tmax), minimum temperature (Tmin), precipitation (Precip), and insolation (Radiation) were used to investigate climatic impact on phenology. And the dataset was obtained from the Data Assimilation and Modeling Center for Tibetan Multi-spheres (ftp://hpcc.itpcas.ac.cn/Data/DAT-31.0002.02.16.NG_ITPCAS-CCMFD_B_v1.6), institute of Tibetan Plateau