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Increasing altitudinal gradient of spring vegetation phenology during the last decade on the Qinghai–Tibetan Plateau

Miaogen Shen[a], Gengxin Zhang[a,*], Nan Cong[b], Shiping Wang[a], Weidong Kong[a], Shilong Piao[a]

[a] Laboratory of Alpine Ecology and Biodiversity, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China
[b] Department of Ecology, College of Urban and Environmental Sciences, Peking University, Beijing 100871 China

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ABSTRACT

Spring vegetation phenology in temperate and cold regions is widely expected to advance with increasing temperature, and is often used to indicate regional climatic change. The Qinghai–Tibetan Plateau (QTP) has recently experienced intensive warming, but strongly contradictory evidence exists regarding changes in satellite retrievals of spring vegetation phenology. We investigated spatio-temporal variations in green-up date on the QTP from 2000 to 2011, as determined by five methods employing vegetation indices from each of the four sources: three Normalized Difference Vegetation Index (NDVI) from the Advanced Very High Resolution Radiometer (AVHRR), Système Pour l'Observation de la Terre (SPOT), MODerate resolution Imaging Spectroradiometer (MODIS), and the Enhanced Vegetation Index (EVI) from MODIS. Results indicate that, at the regional scale, all vegetation indices and processing methods consistently found no significant temporal trend (all $P > 0.05$). This insignificance resulted from substantial spatial heterogeneity of trends in green-up date, with a notably delay in the southwest region, and widespread advancing trend in the other areas, despite a region-wide temperature increase. These changes doubled the altitudinal gradient of green-up date, from 0.63 days 100 m^{-1} in the early 2000s to 1.30 days 100 m^{-1} in the early 2010s. The delays in the southwest region and at high altitudes were likely caused by the decline in spring precipitation, rather than the increasing spring temperature, suggesting that spring precipitation may be an important regulator of spring phenological response to climatic warming over a considerable area of the QTP. Consequently, a delay in spring vegetation phenology in the QTP may not necessarily indicate spring cooling. Furthermore, the phenological changes retrieved from the widely used AVHRR NDVI differed from those retrieved from SPOT and MODIS NDVIs and MODIS EVI, necessitating the use of multiple datasets when monitoring vegetation dynamics from space.

1. Introduction

The Qinghai–Tibetan Plateau (QTP) has experienced significant warming during the past three decades, by approximately 0.4 °C per decade (Dong et al., 2012; Wang et al., 2010). It has been suggested that a warming climate over the QTP could induce extensive ecological and environmental changes (Chen et al., 2013), such as enhancing vegetation productivity (Piao et al., 2012; Wang et al., 2012; Xu et al., 2011) and ecosystem respiration (Lin et al., 2011; Tan et al., 2010), loss of species richness (Klein et al., 2004; Wang et al., 2012), advancing spring phenology (Zhang et al., 2013b), glacier retreat (Yao et al., 2012), and thawing of permafrost (Cheng and Wu, 2007; Wu et al., 2013). However, the magnitude and speed of climatic warming and its spatio-temporal variability remain poorly documented. In particular, the climatic warming has been suggested to be more intensive at higher altitudes, as indicated by both meteorological observations (Liu and Chen, 2000) and a climate model (Chen et al., 2003). The suggested stronger warming at higher altitudes, however, was not found in further studies (Kang et al., 2010; Qin et al., 2009; You et al., 2010). The characterization of temperature change over the QTP is greatly limited by the sparse distribution of meteorological stations (Qin et al., 2009), e.g. only around 100 stations (some of which only started their observations in the 1990s) spread over 2.5×10^6 km^2 and no stations located over 4800 m above sea level (a.s.l.) (Qin et al., 2009). Interestingly, the spring phenological advance was found to be stronger in the areas where there is a greater spring warming trend in temperate and cold regions (Jeong et al., 2011a; Menzel et al., 2006; Root et al., 2003). Over the QTP, it was also found that temperature was a major determinant of spatio-temporal changes in green-up date of the alpine vegetation, and the responses in green-up date were stronger at the altitudes with greater temperature changes

* Corresponding author. Tel.: +86 10 84097071; fax: +86 10 84097079.
E-mail address: zhangg@itpcas.ac.cn (G. Zhang).

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(Piao et al., 2011). Hence, a quantification of spatial correlation between the temporal trend of green-up date and that of temperature may mirror the spatial pattern of the spring warming over the QTP, especially at altitudes higher than 4800 m a.s.l.

The QTP has an average altitude higher than 4000 m a.s.l. (Tang et al., 2009), and thus has a climate that is much colder than that of lowlands at the same latitude. The alpine vegetation of the QTP has a much shorter growing season, mainly because of the later onset of the spring green-up (Zhang et al., 2004, 2006). Hence, the spring vegetation phenological changes on the QTP may have relatively stronger influences on its carbon cycling, because annual vegetation carbon uptake is strongly limited by growing season length and spring phenology (Churkina et al., 2005; Jeong et al., 2012; Piao et al., 2007; Richardson et al., 2009). Furthermore, shifts in the spring vegetation phenology may feed back into regional climate by altering the land-atmosphere energy exchange (Chapin et al., 2008; Jeong et al., 2009; Peñuelas et al., 2009; Richardson et al., 2013; Zhang et al., 2011). For example, Zhang et al. (2011) found that spring vegetation activity on the QTP substantially influenced summer rainfall in many regions of East Asia. On the other hand, spring phenology can affect the livelihoods of QTP residents, because their traditional nomadic lifestyle can be adversely affected when livestock suffer poor grazing due to a lack of forage in spring when the green-up onset is delayed (Ding et al., 2007; Xue et al., 2005). However, we have not yet acquired an explicit understanding of the role of spring phenology in regulating the climatic and ecological dynamics of the QTP, nor of how these dynamics control the forage production that is vital for the wellbeing of local people. A starting point for addressing these issues is to accurately quantify the spatio-temporal changes in the spring phenology.

The spring phenology of the QTP vegetation has also been shown to be sensitive to temperature changes (Cong et al., 2012; Piao et al., 2011; Wang et al., 2013). In response to the fast temperature increase during the 1980s and 1990s (Dong et al., 2012; Liu and Chen, 2000; Yao et al., 2000; You et al., 2013), the spring phenology of QTP vegetation showed great advances (Jin et al., 2013; Piao et al., 2011; Shen et al., 2011; Yu et al., 2010; Zhang et al., 2013b). However, assessments of the spring vegetation phenological changes on the QTP are heavily dependent on remote sensing data, owing to the lack of ground-based observations. Considerable differences exist with regard to the phenological changes found by different studies on the QTP over the past decade. For example, Zhang et al. (2013a,b) found that the onset of spring green-up continuously advanced during this period, while other studies found no such advance (Shen, 2011; Shen et al., 2013). Many factors can introduce uncertainties into satellite-based determinations of vegetation phenology over the QTP, such as data sources, retrieval methods, and data preprocessing methods such as removing the snow cover effect on the NDVI (Cong et al., 2012; Shen et al., 2013; Wang et al., 2013; White et al., 2009; Zhang et al., 2013b). Therefore, multiple datasets and methods are needed to systematically assess the changes in spring vegetation phenology.

Furthermore, previous studies have shown that the spring temperature changes vary widely between different areas of the QTP (Dong et al., 2012; Piao et al., 2011; Qin et al., 2009; Shen et al., 2012), and the phenological responses to temperature may also vary among the different areas of the QTP (Shen et al., 2011). In addition, considerable areas of the QTP are characterized by arid and semiarid climate (Piao et al., 2006a), so spring phenology can be also affected inter-annual variations in spring precipitation (Pangtey et al., 1990; Peng et al., 2010; Shen et al., 2011). As a result, the spring phenology may have experienced different changes across the QTP. However, little is known about the spatial pattern of the spring phenological changes on the QTP during the last decade.

In this study, we firstly assessed temporal changes of spring vegetation green-up onset during the period 2000–2011 by using four greenness vegetation indices from different satellite sensors and five different methods for each of the four indices. We also examined the effect of snow cover on the estimated trends in green-up date from 2000 to 2011. We then examined the spatial pattern of the phenological changes and variations in the associated climatic variables, e.g. the mean temperature and precipitation summation during the 60-day preceding green-up onset. We also discussed the possibility of using the phenological shifts as a proxy for spring temperature change, particularly in areas with no meteorological observations.

2. Materials and methods

2.1. Datasets

The green-up date of each spring from 2000 to 2011 was determined by using two types of satellite-derived greenness vegetation indices: three Normalized Difference Vegetation Index (NDVI) and one Enhanced Vegetation Index (EVI). NDVI was designed to reflect vegetation activity by using information on chlorophyll radiation absorption in the red band and radiation scattering by mesophyll in the near-infrared (NIR) band (Rouse et al., 1974). EVI is a modification of NDVI designed to minimize impacts of soil background and atmospheric noise (Huete et al., 1994; Liu and Huete, 1995). Both NDVI and EVI have been proven to be direct indicators of vegetation activity (Huete et al., 2002; Myneni et al., 1997; Shen et al., 2008, 2010). The datasets used in this study include the 3rd-generation NDVI derived from the Advanced Very High Resolution Radiometer (AVHRR) (Tucker et al., 2005), NDVI from the Système Pour l'Observation de la Terre (SPOT), and NDVI and EVI from the Moderate Resolution Imaging Spectroradiometer (MODIS). The AVHRR NDVI was produced by the global inventory modeling and mapping studies (GIMMS) group at a spatial resolution of 8 km by applying the 15-day maximum-value composition technique (i.e., by selecting the highest NDVI value from each period of 15–16 days) to observations by the AVHRR onboard the NOAA satellites. This NDVI dataset has been corrected for calibration, view geometry, volcanic aerosols, and other effects not related to vegetation changes (Pinzon et al., 2005; Tucker et al., 2004, 2005). The SPOT NDVI dataset was produced at a spatial resolution of 1 km. Compared with the biweekly AVHRR NDVI, the temporal resolution of the SPOT NDVI is 10 days. The effects of satellite orbit shift and sensor degradation have been removed and the atmospheric contaminations of water vapor, ozone and aerosols have also been eliminated (Maisongrande et al., 2004; Rahman and Dedieu, 1994). The MODIS NDVI and EVI datasets (MOD13A1) are produced at 500-m resolution and 16-day compositing period, based on a sophisticated algorithm and quality control (Huete et al., 2002). It has been shown that the vegetation phenology can be estimated with a high precision from time series with temporal resolutions no coarser than 16 days (Zhang et al., 2009).

Daily temperature and precipitation records from 1999 to 2011 for 79 meteorological stations (Fig. 6) across the QTP were provided by the China Meteorological Administration (http://cdc.cma.gov.cn/index.jsp).

2.2. Preprocessing of NDVI and EVI data

On the QTP, there is usually snow cover from fall to the following late spring (Qin et al., 2006), and the duration of snow cover shows substantial spatio-temporal variability (Pu and Xu, 2009). The snow cover often reduces NDVI and EVI values during the non-growing season, which can lead to errors in retrievals of spring phenology (Shen et al., 2013; Zhang et al., 2007). To eliminate this snow-related artifact in the non-growing season NDVI (EVI), for