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Complex responses of spring alpine vegetation phenology to snow cover dynamics over the Tibetan Plateau, China

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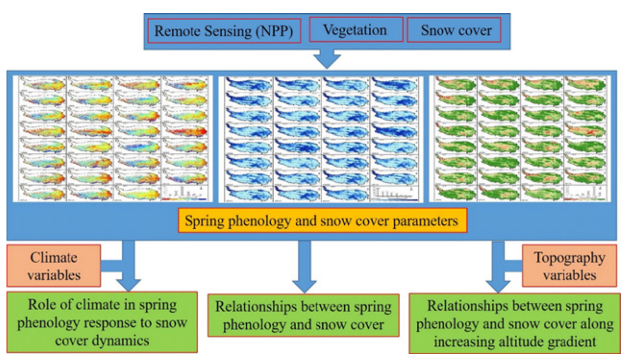
HIGHLIGHTS

- Temporal trends and spatial variations of spring alpine vegetation phenology and snow cover over the Tibetan Plateau
- Responses of spring phenology to snow cover dynamics varied across Tibetan Plateau
- Spatiotemporal response patterns are primarily controlled by local heat-water conditions
- Temperature and precipitation played a profound impact on the responses of spring phenology to snow cover dynamics.

GRAPHICAL ABSTRACT



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ABSTRACT

Snow cover dynamics are considered to play a key role on spring phenological shifts in the high-latitude, so investigating responses of spring phenology to snow cover dynamics is becoming an increasingly important way to identify and predict global ecosystem dynamics. In this study, we quantified the temporal trends and spatial variations of spring phenology and snow cover across the Tibetan Plateau by calibrating and analyzing time series of the NOAA AVHRR-derived normalized difference vegetation index (NDVI) during 1983–2012. We also examined how snow cover dynamics affect the spatio-temporal pattern of spring alpine vegetation phenology over the plateau. Our results indicated that 52.21% of the plateau experienced a significant advancing trend in the beginning of vegetation growing season (BGS) and 34.30% exhibited a delaying trend. Accordingly, the snow cover duration days (SCD) and snow cover melt date (SCM) showed similar patterns with a decreasing trend in the west and an increasing trend in the southeast, but the start date of snow cover (SCS) showed an opposite pattern. Meanwhile, the spatial patterns of the BGS, SCD, SCS and SCM varied in accordance with the gradients of temperature, precipitation and topography across the plateau. The response relationship of spring phenology to snow cover dynamics varied within different climate, terrain and alpine plant community zones, and the spatio-temporal response patterns were primarily controlled by the long-term local heat-water conditions and topographic conditions. Moreover, temperature and precipitation played a profound impact on diverse responses of spring phenology to snow cover dynamics.
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1. Introduction

Since the 1950s, global mean air temperature has increased by 0.6 °C, and the warming trend was more rapid at higher latitudes in the Eurasian continent (IPCC, 2007). Alpine vegetation is characterized by a short growing season, high elevation, snow, low temperature and harsh conditions of the alpine environment. Thus, alpine vegetation is very sensitive to climate change, especially increased temperature (Ide and Oguma, 2013; Whenk et al., 2014). As a result of the recent global warming, spring alpine phenological shifts have been investigated over the high latitudes in the past three decades (Badeck et al., 2004; Cannone et al., 2007; Shen et al., 2014). Such shifts in alpine vegetation phenology may have important consequences for regional or global surface energy balance and the terrestrial carbon cycle (Richardson et al., 2010; Garrity et al., 2011). Concurrently, snow cover plays an important role in alpine vegetation growth. Unfortunately, as a consequence of current climate warming, the decrease in snow cover and earlier snowmelt have been detected from different data records starting in the 1980s over the high latitudes (Simpson et al., 1998; Dery and Brown, 2007). Changes in snow cover have important impacts on the alpine vegetation ecosystems. So improving our ability to accurately describe the responses of alpine vegetation ecosystems to snow cover dynamics may enhance our understanding of changes in terrestrial ecosystems respond to global warming.

The Tibetan Plateau (TP), the highest plateau of the earth, is located in the central part of the troposphere in the mid-latitude westerlies, and is regarded as the Earth's third pole. The mean annual temperature on the plateau is only 1.6 °C, with >60% of the plateau is covered by natural alpine grasslands (alpine steppe and meadow), and >13.3% of the plateau is covered by permanent snow (Bingrong et al., 2006; Pu et al., 2007). TP is one of the most sensitive regions to climate change. Over the past three decades the plateau has experienced significant warming trends (0.13 °C/year in winter, 0.04 °C/year in annual mean) (Liu and Chen, 2000; Du et al., 2004), and this warming is predicted to continue in the 21st century (IPCC, 2007). Thus, the plateau's alpine ecosystems and snow cover are inherently fragile and instable, making them especially vulnerable to global warming and leading diverse responses to climate warming across the plateau.

In recent years, some previous studies have reported different phenological responses in magnitude and even in direction (i.e., advance vs. delay in the date) to climate warming in the TP by using time-series of the satellite-derived vegetation index (VI). For example, Piao et al. (2011) reported that there has no statistically significant trend of the beginning of growing season (BGS) during 1982–2006. Another study found a BGS delay from 1998 to 2003 and an advancement from 2003 to 2009 (Shen, 2011). However, Zhang et al. (2013) reported the BGS advanced on average by $1.04\ d \cdot y^{-1}$ from 1982 to 2011. These varying results showed the environmental complexity of the alpine vegetation in the TP. Major environmental factors controlling alpine phenology include temperature (Piao et al., 2011; Shen, 2011), snowmelt (Yoshie, 2011) and photoperiod (Körner and Basler, 2010). In addition, previous studies also showed that snow cover over the TP has an acceleration of snow melting and changing snowfall amounts caused by increasing air temperature (Qin et al., 2006; Pu et al., 2007; Ma et al., 2011). The dynamics of snow cover will inevitably affect the spring phenology of alpine vegetation over the TP (Wang et al., 2013; Paudel and Andersen, 2013; Zeng and Jia, 2013).

The main objectives of this study were to: (1) quantify the temporal trends and spatial heterogeneity of spring alpine vegetation phenology and snow cover over the TP; (2) assess the relationships between spring alpine vegetation phenology and the timing of snow cover across the plateau over the past three decades (1983–2012); and (3) examine the underlying mechanisms of alpine spring phenology response to snow cover dynamics. Achieving these objectives will improve our understanding of alpine vegetation dynamics and their connections with the cold environment, enhance our ability in predicting the magnitude and direction of spring phenology, and associate changes in the structure and functioning of the alpine ecosystems.

2. Materials and methods

2.1. Data source and pre-processing

2.1.1. NDVI dataset from GIMMS

The $NDVI_{3g}$ data with a spatial resolution of 0.083° and a temporal resolution of a 15-day interval were obtained from the NASA Global Inventory Modeling and Mapping Studies (GIMMS) group (available at http://glcf.umd.edu/data/gimms/). The data were derived from the AVHRR instrument onboard the NOAA satellite series 7, 9, 11, 14, 16, and 17 for the time period from January 1983 to December 2012, and these data had been corrected for calibration, solar geometry, heavy aerosols, clouds and other effects not related to vegetation change (Tucker et al., 2005; Pinzon et al., 2005).

2.1.2. Surface reflectance dataset from AVHRR

The primary data sets in this study were the Advanced Very High Resolution Radiometer (AVHRR) archival reflectance products. These data sets were developed by Long Term Data Record (LTDR) project and distributed through NASA's Goddard Space Flight Center (available at http://ltdr.nascom.nasa.gov/cgi-bin/ltdr/ltdrPage.cgi). The AVHRR archival reflectance products (AVH09C1-version3), with a 0.05° spatial resolution and daily surface reflectance from 1981 to 2011, were generated based on atmospheric correction using Rayleigh scattering, ozone, water vapor and aerosol corrections, and masked out clouds and heavy aerosols (Pedelty et al., 2007).

2.1.3. Climate data, vegetation cover and topography dataset

To validate snow cover products and evaluate the climate conditions related to vegetation phenology and snow cover dynamics, the climate data was used in this study. The climate data set was acquired from the China Meteorological Data Sharing Service System of the China Meteorological Administration (available at http://data.cma.cn/). The climate data are available at 6 h intervals (4-times daily). Three climate variables were acquired: mean daily air temperatures, daily rainfall and sunshine hours. To analyse the phenology variations at the biome level, the vegetation cover characteristics data were acquired from a digitized 1:1,000,000 vegetation map of the TP (Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, 1992). The plateau's vegetation types were regrouped into the following 10 types: evergreen broadleaf forest, deciduous broadleaf forest, mixed forest, shrubland, swamp and barren land, steppe, brushwood, alpine meadow and tundra, sparse alpine vegetation and cultivated land (Fig. 1). The topography data were obtained from the United States Geological Survey (USGS) produced a global digital elevation model (DEM) with a horizontal grid spacing of 30 arc-sec (approximately 1 km) (GTOPO30, available at https://lta.cr.usgs.gov/GTOPO30).

2.1.4. Preprocessing of NDVI time-series data

AVHRR NDVI datasets are processed to reduce the cloud and atmospheric effects before data analyses. The cloud filtering function of the maximum value composition (MVC) was applied to the NDVI data time series. However, there is still some cloud contamination after filtering. To eliminate errors caused by clouds, snow and ice contamination, we further applied a Savitzky-Golay filtering procedure to each annual NDVI cycle for smoothing and reconstructing the NDVI time series, as described by Chen et al. (2004).

2.2. Determination of phenological metrics

Several methods have been developed to detect the phenophases (greenup, maturity, senescence, and dormancy) of vegetation phenology based on NDVI data, such as NDVI thresholds (Lloyd, 1990; White

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