Agricultural and Forest Meteorology 220 (2016) 30–37

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Thermal growing season and response of alpine grassland to climate variability across the Three-Rivers Headwater Region, China

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ARTICLE INFO

Article history:
Received 10 July 2015
Received in revised form 10 December 2015
Accepted 12 January 2016

Keywords:
Thermal growing season
Actual growing season
Alpine grassland
Climate variability
The Three-Rivers Headwater Region

ABSTRACT

Daily temperature data from 1960 to 2013 and field-observed phenology data were used to investigate the spatiotemporal changes in thermal growing season and their relationship with the response of alpine grassland to climate variability in the Three-Rivers Headwater Region (TRHR) during the recent decades. We found a significant extension of the thermal growing season by 8.3 d per decade ($p < 0.01$) between 1986 and 2013 due to the combination of earlier start (tGSS; −4.1 d per decade, $p < 0.01$) and delayed end (tGSE; 4.2 d per decade, $p < 0.01$) of the thermal growing season. However, earlier tGSS and delayed tGSE were weakened between 2000 and 2013, compared to that between 1986 and 1999, in association with changes in seasonal temperature. Our results also suggested that earlier start of actual growing season (aGSS) was associated with the increasing winter and spring temperature; while the end of actual growing season (aGSE) was triggered by summer temperature and precipitation; and earlier and delayed of aGSE were associated with the increasing summer temperature and precipitation, respectively. Additionally, earlier tGSS was associated with an earlier aGSS response to increased temperature, while delayed tGSE was associated with earlier aGSE. Thus, the actual growing season possibly move forward rather than extended in length, in contrast to the extension of the thermal growing season due to the ongoing warming.

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1. Introduction

The thermal growing season, which refers to the entire period during which plant/vegetation growth can occur (Carter, 2008; Linderholm, 2006), is closely correlated with changes in temperature. It is widely recognized that the changes in the thermal growing season is a highly sensitive indicator of the terrestrial ecosystem response to climate change (Shen et al., 2012), and previous studies have suggested that a climate-induced change in the length of the thermal growing season (tGSL) has already occurred (Schwartz et al., 2006; Walther et al., 2002). The changes in tGSL can also regulate climate change through the exchange of carbon and water with the atmosphere and variations in albedo (Liu et al., 2014). Currently, tGSL is of substantial interest, as any variation in this parameter can highly affect ecosystem function and carbon sequestration, possibly resulting in changes in the amplitude of the annual cycle of CO_2 (Goulden et al., 1998; Keeling et al., 1996; Myneni et al., 1997; Piao et al., 2007; White et al., 1999). Therefore, the indices of the thermal growing season, such as start (tGSS), end (tGSE), and tGSL, are important parameters for terrestrial ecosystems, and their study is important for investigating climate change.

During the recent decades, an increasing number of studies described the changes in tGSL across many regions of the world (Feng and Hu, 2004; Linderholm et al., 2008; Liu et al., 2010; Menzel, 2003; Peñuelas and Filella, 2001; Sparks et al., 2009). A significant extension of the thermal growing season was observed throughout major parts of the Northern Hemisphere mid-latitudes during the 20th century, associated with increasing temperatures (Frich et al., 2002). However, large discrepancies exist in the magnitudes and trends of tGSL reported in different studies, owing to differences in species, study areas, study periods, and data sets. Linderholm et al. (2008) reported a general increase in tGSL in the Greater Baltic Area, while the most considerable change was recorded in the spring. In China, Liu et al. (2010) found that tGSL increased by 6.9–8.7 d between 1955 and 2000, mainly due to the earlier

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http://dx.doi.org/10.1016/j.agrformet.2016.01.015
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spring. Similarly, a study in China indicated that tGSL increased by 2.3 d per decade in northern China between 1951 and 2007, mainly due to the earlier tGSS (−1.7 d per decade) (Song et al., 2010). Furthermore, regional scale studies based on meteorological data from high altitudes have found a significant positive trend in tGSL (3.29 d per decade), caused by an earlier tGSS (Dong et al., 2012). Several recent studies have reported the different role of tGSS and tGSE in the extension of tGSL in the Northern Hemisphere, with a combination of earlier tGSS and delayed tGSE in Eurasia, and a significantly delayed tGSE in North America (Barichivich et al., 2012). These studies helped us to better understand the changes in tGSL across different scales, investigation periods, and data sets.

It should be noted that numerous studies have investigated tGSL (Liu et al., 2006), mainly focusing on the spatiotemporal variations of the thermal growing season (Dong et al., 2012; Linderholm et al., 2008; Song et al., 2010) or the possible mechanism underlying the changes in the thermal growing season (Irannezhad and Kløve, 2015). However, few studies have reported the changes in the pattern of tGSL or the variability in the trend of tGSS and tGSE during different periods in the recent decades. Additionally, the relationship between the thermal growing season and the response of alpine grassland to climate variability (expressed by actual growing season) that significant influences the net carbon uptake in terrestrial ecosystems is also not fully understood. A previous study investigated the relationship between the thermal growing season and the timing of biospheric carbon uptake, reflecting the actual growing season and found that the extension in tGSL did not lead to an extension in the period of biospheric carbon uptake (Barichivich et al., 2012). Thus, the relationship between the thermal growing season and the actual growing season needs further investigation, in order to acquire more robust conclusions.

In the recent decades, a significant warming trend was observed on the Tibetan Plateau (Zhang et al., 2013), which is known as the Earth's third pole and is regarded as a very sensitive area to climate change (Liu et al., 2008). Meanwhile, the Tibetan Plateau is the highest and largest plateau on Earth and has significant spatial differences in vegetation types and climate conditions. Thus, studies on the relationship between the thermal growing season and the response of the actual growing season to climate variability in sub-regions of the Tibetan Plateau are needed. The primary objective of this study was to investigate the spatiotemporal pattern and trend of the thermal growing season across the Three Rivers Headwater Region (TRHR) between 1960 and 2013, and further discuss the response of alpine grassland to climate variability. To achieve this goal, we first investigated the spatiotemporal variability of the thermal growing season based on air temperature. Then, we used the partial least squares (PLS) model to explore the response of the alpine grassland actual growing season to climate variability using field-observed phenology data records from three agro meteorological stations.

2. Material and methods

2.1. Study area

The TRHR located in the hinterland of the Tibetan Plateau is the watershed of the Yangtze, Yellow, and Lancang Rivers (Fig. 1). The region is known as the 'Chinese water tower' because of its high average altitude of more than 4000 m a.s.l. (Liu et al., 2006; Zheng, 1996). Generally, the annual mean temperature in the TRHR is less than 10 °C, and a negative trend of precipitation exists from southeast to northwest. The main vegetation type is alpine grassland, including meadow and steppe (Liu et al., 2014).

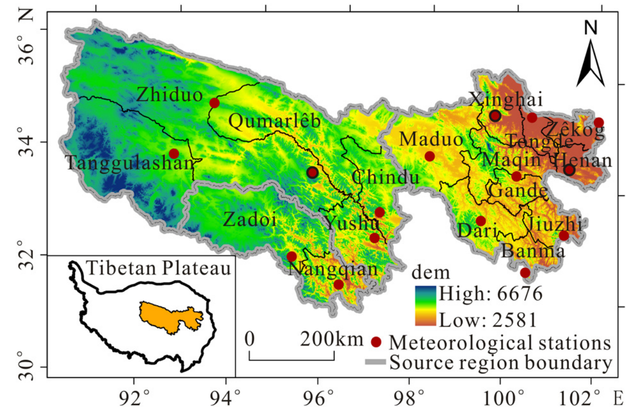

Fig. 1. Study area and distribution of the meteorological stations in the Three-Rivers Headwater Region. The black circles indicate sites with both meteorological and agro-meteorological stations.

2.2. Climate and phenological data sets

Data on the mean daily air and soil temperature collected from the China Meteorological Administration between 1960 and 2013 were obtained from 16 meteorological stations in the TRHR. In order to increase station density and obtain spatial patterns from a higher number of records, relative short temperature data records were also included. For example, the temperature data record of station 3 is between 1999 and 2013, where that for station 4 and 11 are between 1991 and 2013. Raw climate data was transformed using a 5-d running average to eliminate the influence of abnormal values.

In order to investigate the relationship between tGSS and tGSE and atmospheric oscillations, seven different teleconnection and oscillation indices were considered in this study, including the Arctic Oscillation (AO), the North Atlantic Oscillation (NAO), the Tibet Plateau Index (TPI), the Pacific/North American Pattern (PNA), the Southern Oscillation Index (SOI), the Western Pacific Subtropical High-West extension (WPSH-W), and the Western Pacific Subtropical High-Intensity (WPSH-I).

Field data on start (aGSS) and end (aGSE) of actual growing season were collected from three agro-meteorological stations (Qumarlêb station, Henan station, and Xinghai station) across the TRHR between 2000 and 2010. Each agro-meteorological station is a fenced area of 100 m × 100 m. The species-specific phenological observations are carried out for ten individual herbaceous every 2 days by professionals according to uniform observation criteria (Chen et al., 2015). According to the observation criterion, the green-up date is identified when 50% of individual herbaceous plants display green leaves that grow up to one centimeter in spring, whereas the dormancy date is identified when 50% of individual herbaceous plants display yellow leaves in autumn (China Meteorological Administration, 1993). The detail information of each agro-meteorological station is listed in Table 1.

2.3. Methods

There is no universally accepted definition of the thermal growing season; therefore, inconsistencies in tGSL changes are not only due to the regional differences in climates, but also to various definitions of tGSS, tGSE, and tGSL adopted in different studies. Generally, tGSS and tGSE are defined either by single-value thresholds of the mean or minimum daily air temperature (Menzel, 2003) or by threshold temperatures within a predefined number of days. For example, Frich et al. (2002) defined tGSL as the length of a period at the beginning of which daily temperatures remain above

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