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# Asymmetric effects of daytime and nighttime warming on spring phenology in the temperate grasslands of China

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ABSTRACT

Understanding the spring phenology of temperate grasslands and its response to climate change are crucial for diagnosing the responses of ecosystem to regional climate change and projecting regional ecosystem carbon exchange. Using NDVI data from 1982 to 2015, this study investigated the changes of the start date of the vegetation growing season (SOS) for the temperate grasslands of China, and explored the possible effects of average monthly $T_{max}$, $T_{min}$ and total precipitation on the SOS across different grassland vegetation types. We improved on prior studies of climate change in China's temperate zone by focusing only on grasslands unchanged over this extended study period. The results showed that the SOS significantly advanced at a rate of 1.84 days/decade from 1982 to 2015, controlled mainly by spring precipitation and spring and winter temperatures, with differing degrees of influence among vegetation types. On average, an increase of 10 mm in spring precipitation would advance SOS by 1.7 days across the temperate grasslands of China. Although warmer temperatures generally led to advanced SOS, this study revealed for the first time that the seasonal effects of daytime and nighttime warming on the SOS of temperate grasslands in China were asymmetric, with $T_{max}$ more influential in winter and $T_{min}$ more influential in spring. An increase of 1 °C in winter $T_{max}$ and spring $T_{min}$ would advance SOS by 0.42 and 1.34 days, respectively, compared with effects of 0.24 or 0.64 days for 1 °C increases in winter $T_{min}$ or spring $T_{max}$. Given the global asymmetry in daytime and nighttime warming, this study highlights the asymmetric effects of daytime and nighttime warming on the SOS of temperate grasslands in China, and suggests that the impacts of seasonal $T_{max}$ and $T_{min}$ should be considered separately in the SOS modules of terrestrial ecosystem models for temperate grasslands.

## 1. Introduction

Spring phenology is an important indicator of vegetation dynamics and plays an important role in vegetation activity and ecosystem functions (Zhang et al., 2004; Piao et al., 2007; Richardson et al., 2009; Cong et al., 2013; Melaas et al., 2013; Liu et al., 2016b; Wu et al., 2016; Donnelly et al., 2017; Liu et al., 2017). The start date of the vegetation growing season in spring (start of season, or SOS) has been determined from satellite data in recent years (Liang et al., 2011, 2014; Shen et al., 2011; Zeng et al., 2011; Cong et al., 2012, 2013; Garonna et al., 2014; Karlsen et al., 2014; Liu et al., 2014; Zhou et al., 2014; Fu et al., 2015b; Piao et al., 2015; Shen et al., 2015a; Zhang et al., 2015; Liu et al., 2016a; Shen et al., 2016a; Verger et al., 2016; Wu et al., 2016; Vrieling et al., 2017). Variations in the SOS can have some effects on the carbon cycle of terrestrial ecosystems, and can alter land surface energy (Donnelly et al., 2011; Richardson et al., 2013; Shen et al., 2015b; Yang et al., 2017). The SOS is very sensitive to climate change, and an understanding of changes of the SOS in response to climate is crucial for assessing the responses of ecosystem to climate change and predicting future ecosystem dynamic (Badeck et al., 2004; Piao et al., 2006a, b; Körner and Basler, 2010; Zeng et al., 2011). In temperate regions, the SOS of vegetation is significantly controlled by climate factors such as temperature and precipitation (Piao et al., 2006a, b; Cong et al., 2012). However, these relationships between the SOS and climate could vary significantly across different areas and vegetation types (Donnelly et al., 2006, 2015; Cong et al., 2012; Zhou et al., 2014; Ding et al., 2015, 2016; Liu et al., 2016a). China's temperate grasslands constitute the third largest grassland area in the world (Lee et al., 2002) and have

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experienced dramatic climatic change over the past several decades (Shen et al., 2017), significantly affecting the spring phenology. Many studies have investigated the impacts of temperature and precipitation on SOS across the temperate grasslands of China (Piao et al., 2006a, b; Cong et al., 2013; Wu et al., 2016), but prior studies did not compare changes in the SOS across different grassland vegetation types. In recent years, many studies have found different responses of SOS to climate change in different grassland ecoregions of the Tibetan Plateau (e.g. Liu et al., 2014, 2016a, b; Ding et al., 2015, 2016; Wang et al., 2015; Zhang et al., 2015; Zhu et al., 2017). Considering the relationships between the SOS and climate could vary across different vegetation types, the possible effects of climate on the SOS across different temperate grassland vegetation types in China should be further investigated.

A recent study found that increasing daytime maximum temperature ($T_{max}$) has had a greater impact on the SOS than has increasing night-time minimum temperature ($T_{min}$) in the Northern Hemisphere (Piao et al., 2015). It receives great attention because that $T_{min}$ increased faster than $T_{max}$, resulting in a decreasing diurnal temperature range, during the past decades in most parts of the world (IPCC, 2013). In some regions, future climate change might increase the diurnal temperature range (Shen et al., 2014a), which also has complex effects on the phenology. Piao et al., (2015) speculated that daytime $T_{max}$ rather than nighttime $T_{min}$ might fulfill more efficiently the accumulation of heat needed to unfold leaves, and would be more responsible for plant carbon fixation and thus the onset of green-up since plant photosynthesis only occur during the daytime. On the Tibetan Plateau, however, Shen et al (2016a) found that changes in the SOS were more strongly associated with warming winter $T_{min}$, rather than $T_{max}$. This may be because higher $T_{min}$ could alleviate frost damage, but higher $T_{max}$ could exacerbate drought effects over the cold and dry areas (Yu et al., 2010; Shen et al., 2016a). Compared with the cold and dry Tibetan Plateau, the temperate grassland region of China is warmer, with a drier, arid and semi-arid climate. To understand the mechanisms by which temperatures influence the spring phenology of vegetation, it is crucial to investigate the separate impacts of daytime and nighttime warming on the SOS across the temperate grasslands of China. In addition, considering the possible different effects of seasonal temperature on spring phenology (Yu et al., 2010; 2012), the seasonal response of SOS to daytime and night-time warming should also be considered.

In this study, we investigated changes in the SOS across the temperate grasslands of China, detected using normalized difference vegetation index (NDVI) derived from AVHRR satellite imagery from 1982 to 2015. We explored the possible effects of average monthly temperatures (including $T_{mean}$, $T_{max}$ and $T_{min}$) and total precipitation on the SOS across different grassland vegetation types. Different from previous studies, this study only analyzed the unchanged (belonging to the same land use type) temperate grasslands during the study period in order to minimize the possible impacts of land-use change on SOS results. The findings of this study can aid in diagnosing the responses of ecosystems to regional climate change and further understanding global climate change.

## 2. Materials and methods

### 2.1. Study area

According to the Vegetation Atlas of China (Chinese Academy of Sciences, 2001), China's temperate grasslands are mainly distributed across the Inner Mongolian Plateau, the Songliao Plain and the Loess Plateau (Fig. 1). The elevation of this temperate grassland zone of China ranges from 60 to 4441 m, which is generally lower from west to east. China's temperate grasslands occur in a region with a semi-arid to arid climate. Annual average temperatures in this region vary from −5 °C to 10 °C, and annual precipitation ranges from 35 to 530 mm (Shen et al., 2017). It is reported that annual mean temperature showed a significant increase in China including the temperate grassland region of China

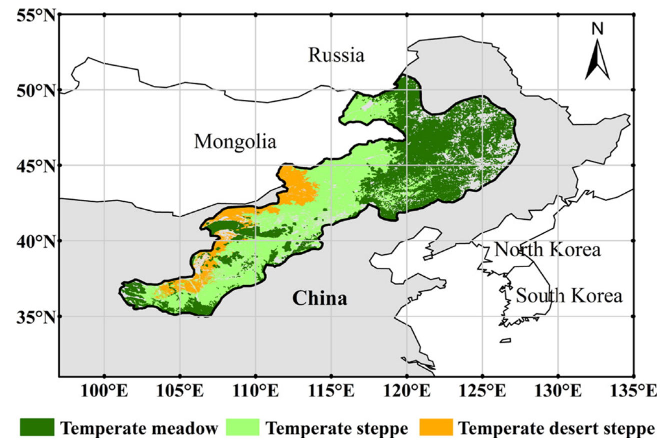


**Fig. 1.** The spatial distribution of grassland vegetation types (unchanged from the 1980s to 2015) in the temperate grassland zone of China.

from 1980 to 2015 (Shen et al., 2018). Over the whole study area of the temperate grassland region in China, annual $T_{max}$ and $T_{min}$ significantly ($P < 0.01$) increased by 0.31 °C/decade and 0.35 °C/decade, respectively, during 1982–2015. Temperate grasslands in this region include three different vegetation types of temperate meadow, temperate steppe, and temperate desert steppe, which are classified in raster land use/cover products of China used in this study.

### 2.2. Datasets and determination of SOS

For this study, we analyzed vegetation phenology evident in data from the Global Inventory Monitoring and Modeling Studies (GIMMS), specifically the GIMMS-3 G version 1 NDVI dataset derived from Advanced Very High Resolution Radiometer (AVHRR) satellite imagery. The dataset spans 1982 through 2015 with a 15-day temporal resolution and an 8 km × 8 km spatial resolution (Tucker et al., 2005, Wang et al., 2017a, b). The GIMMS-3 g NDVI data, processed to minimize errors and biases, have been widely used for investigating long-term changes in vegetation around the globe (e.g. Piao et al., 2006a, b; Cong et al., 2013; Wu and Liu, 2013; Yang et al., 2015; Wang et al., 2017a, b). We also made use of land use and land cover (LULC) maps for two periods (the 1980s and 2015) to detect changes in vegetation types within the study area. The LULC data had a spatial resolution of 100 m × 100 m, and were obtained from the National Earth System Science Data Sharing Platform of China (Shen et al., 2016b). These land use maps were classified into six first levels of land use categories and twenty-five second levels including three grassland vegetation types of temperate meadow, temperate steppe, and temperate desert steppe (Shen et al., 2016b). Gridded meteorological data including monthly mean ($T_{mean}$), maximum ($T_{max}$) and minimum ($T_{min}$) temperature and precipitation from 1981 to 2015, with spatial resolution of 0.5°× 0.5°, were generated from more than 800 meteorological stations throughout China (Yang et al., 2015) based on Kriging interpolation technique (Goovaerts, 1997). In this study, the land use map and climate data were resampled to a spatial resolution of 8 km × 8 km in accordance with the NDVI data.

### 2.3. Analyses

In this study, the Polyfit-Maximum method was used to identify the starting date of vegetation growing season (SOS). The Polyfit-Maximum method treats the period of largest increase of the seasonal NDVI time series as the onset of vegetation growth, and it has been widely used in determining the starting date of vegetation green-up (e.g. Piao et al., 2006a, b; Cong et al., 2012, 2013; Fu et al., 2014a; Wang et al., 2017a, b). For each pixel, the relative change in NDVI is calculated from annual