VARIATION IN GREEN-UP DATE OF *KOBRESIA PYGMAEA* ALPINE MEADOW IN QINGHAI-TIBETAN PLATEAU DURING 1961-2016

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ABSTRACT:

Vegetation phenology in Qinghai-Tibetan Plateau (QTP) has been proved to be more sensitive to climate change. The previous researches have reported divergent phonological responses of alpine vegetation in QTP from the analyses of remote sensing data, thus the demand for further analysis based on long-term observed vegetation data becomes more urgent. In the lack of long-term remote sensing monitoring data and ground observation data, phenology model simulation can be used as an effective remedy. In this study, we used a phenology model (unified model, UM) to simulate the green-up date for *Kobresia pygmaea* alpine meadow, and model evaluation shows that the unified model is able to make reasonable estimation for green-up date derived from satellite observations. Based on the phenology model and its parameters, spatial and temporal changes in green-up dates for *Kobresia pygmaea* alpine meadow in QTP from 1961 to 2016 were simulated, the results indicated that, the variation in green-up date presented an overall insignificant temporal trend with obvious spatial differences; furthermore, complex stage characteristics about the variation in green-up date were also clearly revealed, the period from 1991 to 2005 could be considered as a turning point, before which the trend was mainly in advan[1]ce and after which the trend was mainly in delay.

1. INTRODUCTION

Phenology is an excellent means by which the impact of climate change on vegetation can be detected and measured. The influence of climate changes can be examined using the annual variation in the start dates of phenophases (Roetzer et al., 2000). The unique geographical and environmental backgrounds on Qinghai-Tibetan Plateau (QTP) make it the principle regional driver and amplifier of global climate change(Dong et al., 2012; Che et al., 2014). Alpine vegetation in QTP is characterized by a high elevation, low temperature and harsh conditions of the alpine environment, thus, the plateau's alpine ecosystems is inherently fragile and instable, and numerous studies have shown that alpine vegetation phenology in this region is highly sensitive to climate change (Shen et al., 2011; Dong et al., 2012; Zhang et al., 2013; Ide et al., 2013; Che et al., 2014; Whenk et al., 2014; Wang et al., 2017; Zhu et al., 2018).

As an important indicator of climate change, phenology shifts of alpine vegetation in QTP have been a research focus during the past decade (Shen et al., 2015), previous work based on remote sensing investigations and field observations provided phenological data at different scales (Yu et al., 2010; Zhang et al., 2013; Zhou et al., 2014; Zhu et al., 2017), but up to now, the understanding about its temporal trend and spatial pattern is still insufficient.

In recent years, some previous studies have reported divergent phonological responses from the analyses of remote sensing data in QTP. Some studies suggested that the green-up date of alpine grasslands in QTP has been advanced. Zhang et al. (2013) reported the green-up dates advanced on average by 1.04 day year^{-1} from 1982 to 2011, which was consistent with observed warming in springs and winters (Zhang et al., 2013; Zhang et al., 2015). Cheng et al. highlights the phenological property with an

advancing green-up date for meadow in the eastern Tibetan Plateau from 1982 to 2014 (Cheng et al., 2018).Wang et al. found that the green-up date of grassland in QTP primarily advanced with values of 0-2 days from 1985 to 2010 (Wang et al., 2018). Chang et al. indicated that green-up date was more likely to be advanced in areas where the spring temperature increased at a faster rate from 1982 to 2012 (Chang et al., 2016). Ding et al. reported that from 1999 to 2009, green-up dates of the alpine grassland advanced significantly (six days per decade) in the eastern Plateau (Ding et al., 2013). Li et al. indicated that the green-up date of the alpine grassland in the watershed generally advanced at the rate of 1.4 days decade^{-1} and in local areas showed spatially heterogeneous trends in the period 2000-2016 (Li et al., 2017). Nevertheless, some inconsistent results have been proposed. Shen (2011) found a green-up date delay from 1998 to 2003 and an advancement from 2003 to 2009 (Shen, 2011). Zhao et al. found that the trend of green-up date was postponed in QTP from 2001 to 2014, which was different from most regions of China (Luo et al., 2017). Ganjurjav et al. (2016) proposed that the phenology has advanced in some years and at some locations in QTP since 2000, whereas it has been delayed in others (Ganjurjav et al., 2016). Zhang et al. (2018) and Wang et al. (2019) revealed that turning point of the green-up date metrics was near the year 1998, before which the green-up date advanced and after which the green-up date delayed, and temperature was found to be the dominant meteorological variable impacting phenology (Zhang et al., 2018; Wang et al., 2019). Piao et al. (2011) reported that the vegetation green-up significantly advanced by 0.88 days year^{-1} from 1982 to 1999, but a marginal delaying trend is evidenced from 1999 to 2006 , thus there has no statistically significant trend of the vegetation green-up date from 1982 to 2006 at the regional scale (Piao et al., 2011). Yu et al. (2010) also indicated that during 1982-2006 for meadow and steppe vegetation in QTP, spring phenology

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initially advanced, followed by retreating in the mid-1990s in spite of continued warming (Yu et al., 2010). However, Chen et al. (2015) reported no continuous advancing trends of green-up dates during 1982-2011 according to ground observations, and no turning points in the mid to late 1990s as reported by remote sensing studies(Chen et al., 2015).

These varying results suggest that the response of alpine grassland growth to spatially heterogeneous climate factors maybe complex and non-intuitive in QTP. The above-mentioned discrepancies in research results also call for further analysis based on updated long term observed vegetation data, and the spatiotemporal variations of vegetation phenology and their relations to climatic factors across the QTP could be further researched. In the case of limited remote sensing monitoring and ground observation data, model simulation can be used as an effective remedy.

In view of the complexity of spatio-temporal variations and climate-driven mechanisms of alpine grassland spring phenology in QTP, the objectives of this study are to: (1) parameterize a robust climate-driven phenology model by the aid of NDVI-derived phenology metrics; (2) use the phenology model to characterize the spatio-temporal patterns of regional phenology variations in QTP at long term scale.

2. MATERIALS AND METHODS

2.1 Study area and data

The QTP located in the south of the Asian continent (26°00′12″N-39°46′50″N, 73°18′52″E-104°46′59″E) with an average altitude of more than 4000m, which is the highest plateau in the world and regarded as the Earth's third pole. QTP has complex and diverse physiognomies, and it is a sensitive area of global climate change (Li et al., 2010). Annual mean temperature across most of the QTP is < 0 °C, which results in high temperature-sensitive biological and chemical processes (Shen et al., 2016). A range of evidence has shown that temperature has risen by 0.3-0.4 °C per decade and at about twice the global average over the past five decades (Chen et al., 2015). More than 60% of the plateau is covered by natural alpine grasslands (alpine steppe and meadow), and *Kobresia pygmaea* accounts for about 56% of the alpine meadow types in the Qinghai-Tibet Plateau in area (Zhang et al., 2007), which is suitable for remote sensing monitoring.

Climate data were derived from the National Meteorological Information Center (http://data.cma.cn/). The daily mean temperature at 32 weather stations from 1960 to 2016 was used in this study. The observed phenology data for *Kobresia pygmaea* at 2 meteorological stations from 1991 to 2010 was used to test the robustness of the green-up date derived method based on remote sensing data (Fan et al., 2014). For each year, climate and phenology data dating back to the previous September were compiled for use in the spring phenology models.

The GIMMS NDVI data from the NOAA satellite with 15-day interval and 8-kilometer resolution from 1982 to 2011 were used to derive the green-up dates for *Kobresia pygmaea*. The NDVI data from the products were composited using a 15-day maximum value composite method; thus, for each grid cell, the NDVI data contained 24 values per year, and the 30-year NDVI time-series data contained 720 values. The NDVI time-series data for each weather station were visually selected based on a

1:1,000,000 vegetation map of China (Zhang, 2007) and high-resolution Google Earth data. Specifically, more than three NOAA NDVI pixels with *Kobresia pygmaea* as the dominant species were selected within a 20-km range of each weather station, and then the NDVI values were spatially averaged to represent the NDVI values of each station for further analysis.
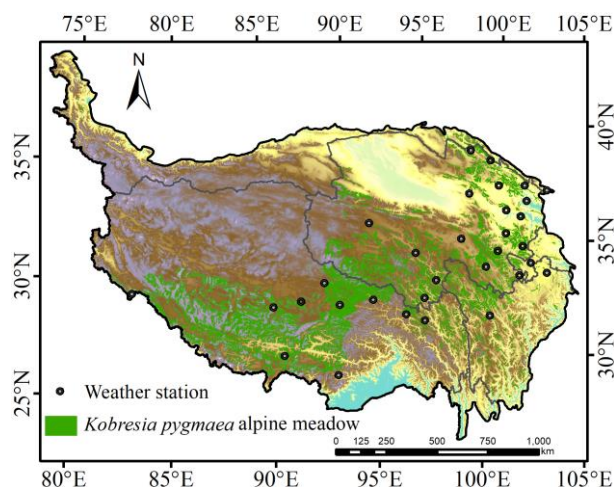

Figure1. The distribution of *Kobresia pygmaea* alpine meadow and the weather stations in QTP

2.2 Methods

2.2.1 Deriving green-up date based on the NDVI time series: The methods for estimating the green-up date from remote sensing data generally involve two processes: reconstructing high-quality vegetation index time-series data through noise removal and computing the green-up date from the reconstructed data. In this study, we first used the Dixon's test (Fan et al., 2013) to detect and remove the noise in original NDVI time serial data. Then we used the double-Gaussian function (Li et al., 2008) to reconstruct the NDVI time series. Finally, we used the maximum slope threshold method (Piao et al., 2006) to derive the green-up date for *Kobresia pygmaea* alpine meadow from the reconstructed NDVI time series. Details about the derivatization method and its verification process can be found in the literature (Fan et al., 2014).

2.2.2 Simulating the Green-up Date with the Unified Phenology Mechanism Model: The unified phenology mechanism model (UM) (Chuine, 2000) was used to simulate the green-up date for *Kobresia pygmaea* alpine meadow. We first used a simulated annealing algorithm (Kirkpatrick et al., 1983) to parameterize the UM based on the NDVI-derived green-up dates and the daily mean temperature data from 1982 to 2001. Then, the internal validations were performed using the green-up dates and the daily mean temperature data from 1982 to 2001, and the external validations were also performed using corresponding data from 2002 to 2011. Finally, we used the parameterized UM to simulate the green-up date for *Kobresia pygmaea* alpine meadow at a regional scale from 1961 to 2016.

3. RESULTS

3.1 Model parameterization using NDVI-derived phenology metrics

The NDVI-derived green-up date and climate data at 32 weather stations from 1982 to 2001 were used to parameterize the

phenology model of *Kobresia pygmaea* alpine meadow. The optimized parameters for the UM are presented in Table 1.

parameters	a_c	b_c	c_c	b_f	c_f
value	0.9332	-28.7125	-30.7441	-0.1406	8.4990
parameters	w	k	C^*	t_c	
value	77.8537	-0.0062	2.2942	208.9	

Table 1. The optimized parameters of the UM for *Kobresia pygmaea*

The response functions of the chilling and forcing effect to daily mean temperature are shown in Figure 2 and Figure 3, respectively. The chilling effect for *Kobresia pygmaea* reaches a relatively strong level between -31°C and -1°C. Lower or higher daily mean temperatures beyond the optimal chilling temperature range would weaken the chilling effect for the breaking of dormancy. The forcing effect for *Kobresia pygmaea* follows a sigmoid curve as the daily mean temperature rises from -28°C to 37°C. The forcing effect becomes valid when the daily mean temperature is above -15°C and increases very rapidly when the daily mean temperature rises from -2°C to 15°C. The growth of *Kobresia pygmaea* started at relatively low temperatures, which could be regarded as the result of its long-term adaptation to the cold environments in QTP.
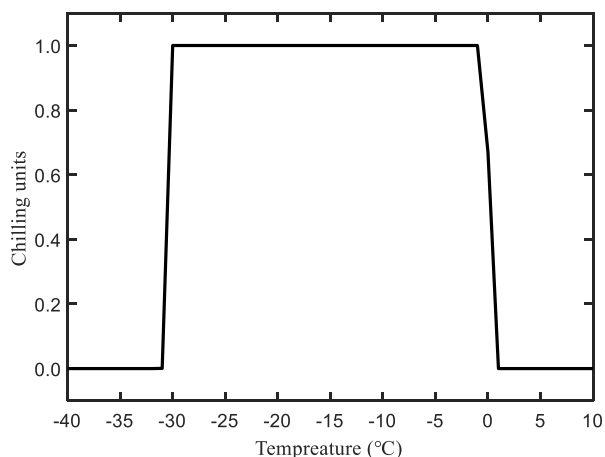

Figure 2. The response functions of chilling effect to daily mean temperature for *Kobresia pygmaea* alpine meadow
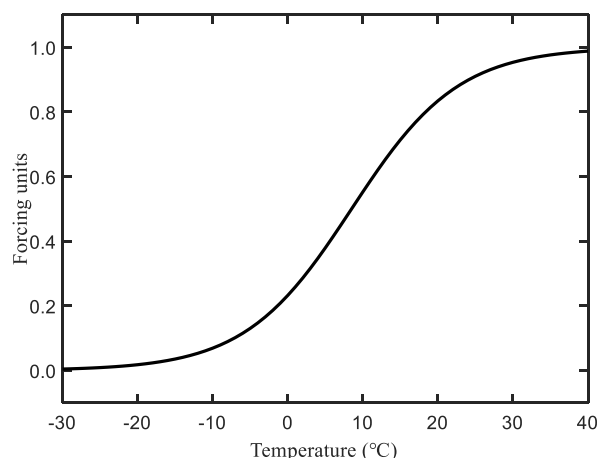

Figure 3. The response functions of forcing effect to daily mean temperature for *Kobresia pygmaea* alpine meadow

3.2 Model validation

The green-up dates derived from satellite observations and phenology model simulations show good agreement (Figure 4, Figure 5), although these green-up dates are defined somewhat differently. When the same data as model parameterization (i.e., daily mean temperature and NDVI data from 1982 to 2001; internal validation) were used in the evaluation, the correlation coefficient and RMSE between the simulated and the NDVI-derived green-up dates were 0.62 (P < 0.0001) and 7.53 days (Figure 4), respectively. If the different data from model parameterization (i.e., daily mean temperature and NDVI data from 2002 to 2011; external validation) were used, the correlation coefficient and RMSE between the simulated and the NDVI-derived green-up dates were 0.61 (P < 0.0001) and 6.87 days (Figure 5). This result shows that, using climate data measured at the weather stations, the UM is able to make reasonable estimations for green-up dates of alpine meadow.
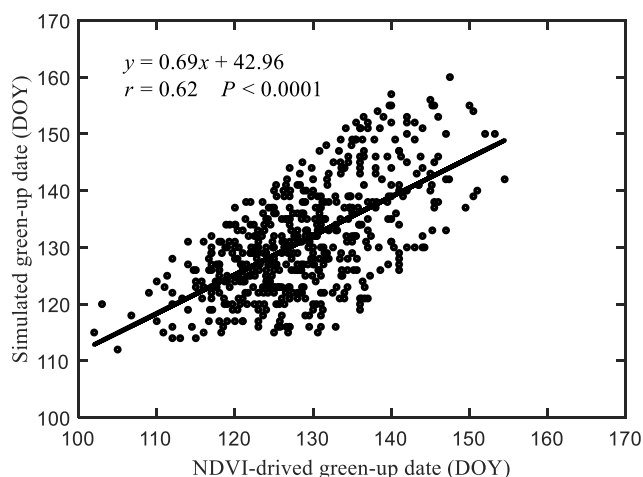

Figure 4. Comparison of model simulated and NDVI-derived green-up dates: internal validation
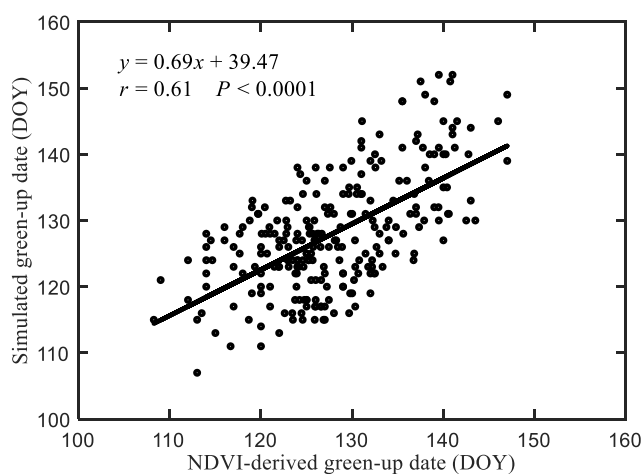

Figure 5. Comparison of model simulated and NDVI-derived green-up dates: external validation

3.3 Spatial and temporal changes in green-up dates

Analysis in Section 3.2 shows that the phenological model based on remote sensing monitoring has reliable accuracy, therefore, in the absence of ground phenological observation and remote sensing monitoring, the UM can be used to study vegetation phenological changes on a large scale and over a long-time span.

Based on the parameterized UM and spatial daily temperature data, the green-up dates of *Kobresia pygmaea* alpine meadow in QTP from 1961 to 2016 were simulated. The interannual variation in green-up dates was also analysed.

As shown in Figure 6a, the green-up dates of *Kobresia pygmaea* alpine meadow across QTP showed an insignificant temporal trend but significant spatial differences during the study period (1961-2016). Although the change in the green-up date over the 56 years did not exceed ± 10 days in most (97.91%) of the pixels, the advancing trend was mainly distributed in the north and middle of the study area, and the delayed trend was mainly distributed in the southeast of the study area. This may be related to the heterogeneous spatial pattern and stage differences in the trends of the green-up dates (Figure 6b, Figure 6c, Figure 6d, Figure 6e).

From 1961 to 1975, significantly advanced trends in green-up date were found in most of the pixels (88.24%), only a small number of pixels (11.76%) in the central and southeast region showed a delayed trend with a value mainly between 0 and 5 days (Figure 6b). Of the advancing trends, 16.17% were between -15 and -10 days, mainly distributed in the southwest of the study area; 29.74% were between -10 and -5 days, mainly distributed in the southwest and northeast of the study area; and 38.33% were between -5 and 0 days, mainly distributed in the central region of the study area.

The spatiotemporal distribution characteristics from 1976 to 1990 (Figure 6c) were similar with that from 1961 to 1975, but the proportion of pixels presenting delayed trend in the central region had been increased. In this time period, advancing trends were found in approximately 67.60% of the pixels, mostly distributed in the southwest and northeast region; while, delayed trends were found in approximately 32.40% of the pixels, mainly distributed in the central and southeast region.

Differing from the previous period (1975-1990), from 1991 to 2005, in the southwest and northeast of the study area, the green-up date appeared a slightly delayed trend mainly ranging from 0 to 5 days, and in the central region, the dominant trend turned from delay to advance (Figure 6d). Overall, in the study area, 41.36% of the pixels showed an advancing trend, and 58.64% of the pixels showed a delayed trend. The distribution characteristics are consistent with some early ground phenology observations, for example, Zhou et al. (2014) found that the green-up date of alpine meadow in some sampling sites (Qumalai and Gande) had advanced from 1990 to 2006 (Zhou et al., 2014). The result means that, during this period (1991-2005), the spatial distribution characteristics of the variation in green-up dates had changed essentially.

In the past ten years (2006-2016), the delayed trend in the green-up date becomes more obvious, a delayed trend was found in almost all of the pixels. Of the delayed trends, 19.33% were between 10 and 15 days, 34.05% were between 5 and 10 days, and 33.90% were between 0 and 5 days (Figure 6e).

In summary, over the past 56 years, the green-up date of *Kobresia pygmaea* alpine meadow in QTP showed an overall insignificant temporal trend and the variation was mainly within ± 10 days, however, significant spatial differences in the variation of green-up date were represented distinctly: in the north and middle of the study area, green-up dates of *Kobresia pygmaea* alpine meadow were advanced, and that in the south of the study area were delayed. Furthermore, complex stage characteristics about the variation in the green-up dates were also found in this study: the period from 1991 to 2005 is the turning point of variations in green-up dates, before which the trend was mainly in advance, and after which the trend was mainly in delay.
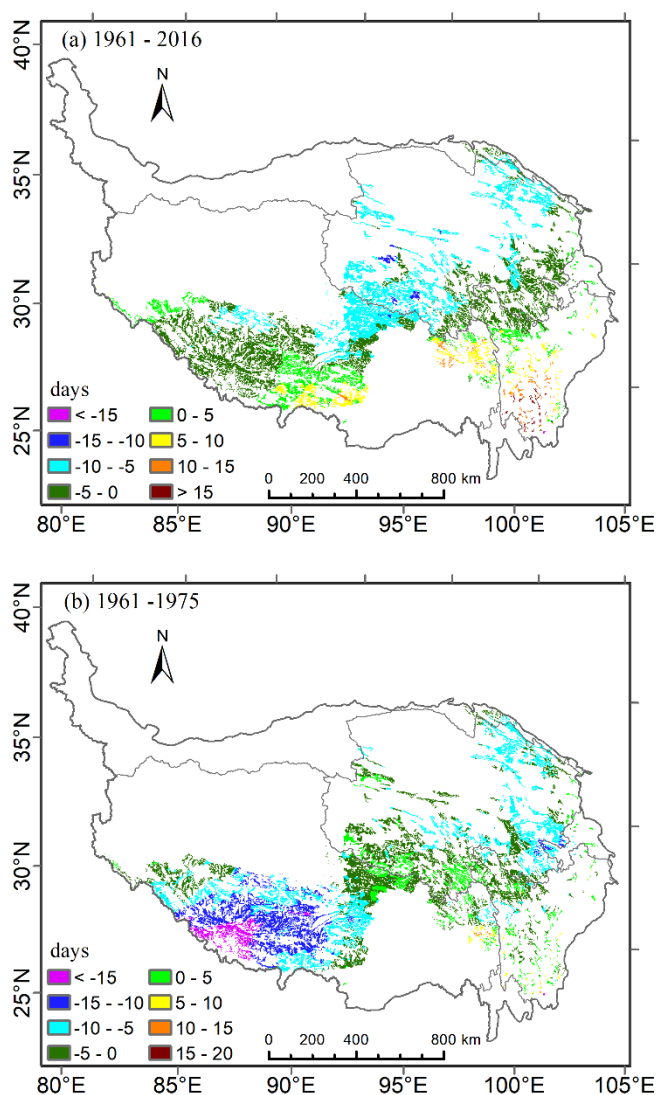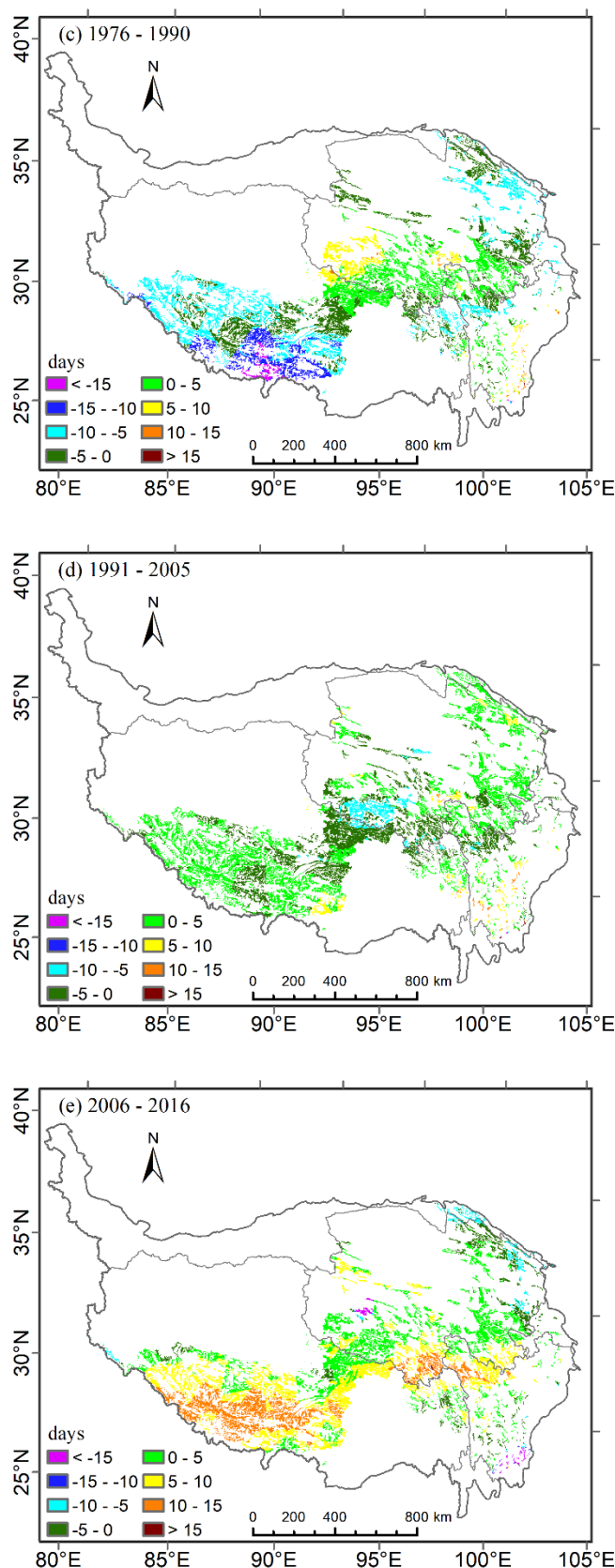
Figure 6. Spatial pattern of the temporal trends in the green-up date from 1961 to 2016.

4. CONCLUSION

In this study, we parameterized a phenology model and characterized the spatio-temporal patterns of *Kobresia pygmaea* alpine meadow in Qinghai-Tibetan Plateau. We carefully processed the green-up dates derived from satellite data and the climate datasets. The unified phenology model was calibrated and evaluated against 30-year satellite observations.

Three main conclusions are drawn from our study. First, for the *Kobresia pygmaea* alpine meadow, the unified phenology model is able to make reasonable estimation in green-up dates derived from satellite observations, therefore, with the help of long-term temperature observation, it could be used as an effective remedy to estimate green-up dates in the lack of long-term remote sensing monitoring and ground observation data. Second, the green-up dates of *Kobresia pygmaea* alpine meadow in Qinghai-Tibetan Plateau from 1961 to 2016 showed an overall insignificant temporal trend, but the variation presented obvious spatial differences from north to south of the study area. Third, in the past 56 years, variation in the green-up dates of *Kobresia pygmaea* has complex stage characteristics during different periods, there has been a turning point from 1991 to 2005, before which the trend was mainly in advance and after which the trend was mainly in delay.

Further research should focus on the issue of various model applications, multiple vegetation, longer time frames and higher spatial resolution. In addition, the effect of more climate factors (such as precipitation, photoperiod, winter snow, etc.) and human factors on phenology change should be carefully researched, and the climate-driven mechanism could be explored gradually by means of appropriate phenology models.

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