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Spatiotemporal variation in alpine grassland phenology in the Qinghai-Tibetan Plateau from 1999 to 2009

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Plant phenology is the most salient and sensitive indicator of terrestrial ecosystem response to climate change. Studying its change is significantly important in understanding and predicting impressively changes in terrestrial ecosystem. Based on NDVI from SPOT VGT, this paper analyzed the spatiotemporal changes in alpine grassland phenology in Qinghai-Tibetan Plateau from 1999 to 2009. The results are enumerated as follows: (1) The spatial distribution of the average alpine grassland phenology from 1999 to 2009 is closely related to water and heat conditions. Accompanying the deterioration in heat and water conditions from southeast to northwest, the start of growth season (SOG) was delayed gradually, the end of growth season (EOG) advanced slowly, and the length of growth season (LOG) shortened gradually. Elevation played an important role in the regional differentiation of phenology, but a dividing line of approximately 3500 m existed. Below this line, the phenology fluctuated irregularly with altitude change, whereas above the line, the phenology is closely related to altitude change. (2) From 1999 to 2009, SOG of the alpine grassland came earlier by six days per decade (R^2=0.281, P=0.093), EOG was late by two days per decade (R^2=0.031, P=0.605), and LOG lengthened by eight days per decade (R^2=0.479, P=0.018). The early SOG, the late EOG, and the extended LOG mainly occurred at the center and east of the Plateau. SOG in most of the Plateau advanced significantly, especially in the eastern Plateau. (3) The inter-annual phenology changes of the alpine grassland in the Qinghai-Tibetan Plateau exhibited significant differentiation at different elevation and natural zones. The inter-annual changes at high altitude were more complicated than that at low altitude. The most significant phenology changes were found in the eastern Qinghai-Qilian montane steppe zone, and non-significant changes occurred in the Southern Tibet montane shrub-steppe zone.

Qinghai-Tibetan Plateau, alpine grassland, phenology, spatiotemporal variation

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Plant phenology refers to the temporal pattern of seasonal leaf development and senescence considering the effects of climate and other environmental factors [1]. It indicates the growth rhythm of plants in adapting to seasonal changes in the environment [2]. Plant phenology not only provides a substantial theoretical and practical significance in farming forecast, agricultural and animal-husbandry production guidance, pest indication, seed introduction and selection, and many other aspects but also serves as an important parameter in land process model and global vegetation model [3–6]. This information is very important in promoting people's understanding of the response of vegetation to climate change and improving the simulation accuracy of mass and energy exchanges between the atmosphere and vegetation [7].

As the best indicator in monitoring the influence of climate on vegetation, plant phenology has become the key point of global-change research [8]. Plant phenology analysis based on remote sensing data shows that the growth season of plants in northern hemisphere has lengthened gradually during the last decades [9–12]. These conclusions are supported by ground observation data. The spring phenophase of most plants in Europe and North America have

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*Corresponding author (email: zhangyl@igsnrr.ac.cn) arrived earlier during the last decade [8,13,14]. Ground phenology observation data in China also showed that the spring phenophase in North China have arrived earlier after the 1980s [15,16]. However, some research findings have also proven that the spring phenophase of plants in many areas in the northern hemisphere changed in the opposite direction in the 1990s, i.e. the spring phenology was delayed with rise in temperature [17–19]. Yu et al. [18] believed that this event was closely related to the temperature rise during winter. In temperate zone, frigid zone, and high-attitude areas, the onset of spring phenophase of many plants is closely related to air temperature in winter and spring. High temperature in winter is not conducive to breaking the dormancy of winter buds and delays spring phenophase.

As the third pole of the world, the Qinghai-Tibetan Plateau has approximately 1521500 km^2 of alpine grasslands (accounting for 59.15% of the total area of 2572400 km^2 [20] in the Qinghai-Tibetan Plateau), one of the important pasture areas in China or even in the entire Asia. The Plateau's ecological process has the unique function of ensuring ecological security of China and East Asia [21,22]. Meanwhile, hydrothermal conditions at the biological limit level make the grassland ecosystem extremely sensitive to climate change disturbance. Currently, the Qinghai-Tibetan Plateau is under an abrupt temperature-rise stage [23]. Research conducted by Li et al. [24] showed that the annual average temperature ramp in the Qinghai-Tibetan Plateau during 1961–2007 was 0.37°C/10 a, obviously higher than the temperature-rise level of the entire country in the past 50 years (0.16°C/10 a)[25]. In addition, the authors also indicated that a consistent temperature-rise trend occurred in different areas of the Plateau, and the degree of warming in winter and spring was evidently higher than that in other seasons. Sudden temperature rise can certainly affect the phenology of alpine grasslands in the Qinghai-Tibetan Plateau. Existing studies prove that the phenology in the Qinghai-Tibetan Plateau is changing significantly. However, different views exist on whether the situation started changing by the end of 1990s [17,18,26].

The current paper mainly focuses on the spatiotemporal change of the alpine grassland phenology in the Qinghai-Tibetan Plateau in the last 10 years and tries to answer several issues. Among them are the following: (1) spatial distribution patterns of phenological multi-year average of alpine grasslands in the Qinghai-Tibetan Plateau in the last 10 years; (2) phenological change trend and spatial distribution pattern in alpine grasslands in the Qinghai-Tibetan Plateau in the last ten years, and (3) phenological change difference before and after the end of 1990s.

1 Data and method

1.1 Data

The current research adopted the time series SPOT-VGT NDVI data set from 1999 to 2009, obtained from the Flemish Institute for Technological Research of Belgium (http://free.vgt.vito.be/). The data set was captured at a spatial resolution of 1 km using the 10-d maximum-value composition (MVC) technique. It has been corrected for geometrical, atmospheric, and sensor degradation, and cloud contamination was removed. The data set projection was finally transformed into GCS-WGS-1984 projection. The vector data of the alpine grassland in the Qinghai-Tibetan Plateau are excerpted from the doctoral dissertation of Zhang (1:100000) [27].

1.2 Method

(1) Preprocessing of time series data. NDVI can manifest the dynamic growth process of ground vegetation. However, data collection and processing are disrupted by various factors, which can greatly affect data quality. Although the data in this research adopt the MVC technique and other treatments, the technique cannot remove the contamination of residual cloud in the subpixel and long-term cloud haze or the other negative effects. Thus, further smooth treatment is necessary because these factors appear at random, causing an unclear curvilinear change trend of the growth season.

The traditional smooth method [28–30] describes the general characteristics of the curve, rather than the cyclicity implied by the curve. Harmonic Analysis of Time Series (HANTS) is a new method used to analyze plant phenology. It fully considers the plant growth cycle and the dual characteristics of the data. Rebuilt time series data based on this method can reflect the true periodic change rules of the curve [31]. The HANTS method is employed in this research for smooth treatment of NDVI data composed within 10 days. The specific steps are described as follows: the original NDVI time series data composed within 10 days are processed first (Figure 1) to obtain two types of data, i.e., NDVI data with temporal resolution of 10 days and NDVI data with temporal resolution of one day. During the processing, the range of valid values is 0–256, with a cycle of 365 and frequency of two (365, 182).

To eliminate the effects of bare soil, sparse vegetation, and evergreen forest, the pixel in this research must meet certain requirements. They are as follows: 1) the average value of NDVI in April-September shall be more than 0.10; 2) the maximum value of annual NDVI shall exceed 0.15; 3) the annual maximum value shall occur between July and September; and 4) the average value of NDVI in winter shall be less than 0.4 [32].

(2) Determination of phenophase. Currently, many scholars put forward different remote sensing phenology extraction methods. They are: 1) threshold method [33,34]; 2) maximum ratio method [18,35]; 3) integration of methods 1) and 2) (requires determining first the phenology threshold according to the maximum ratio and determining the annual occurrence date of such phenology based on the threshold [36,37]); and 4) logistic function or harmonic

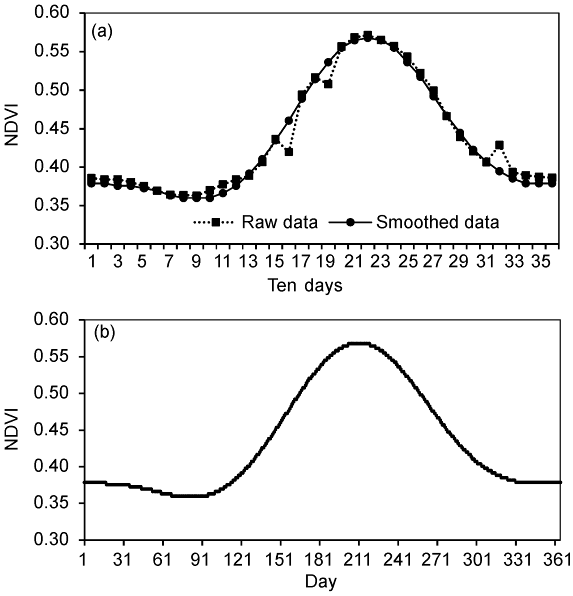

Figure 1 NDVI time series data after HANTS smoothing. (a) Comparison between raw and smoothed NDVI; (b) smoothed and interpolated NDVI with time resolution of one day.

decomposition function, used to determine the turning point of NDVI time series to estimate phenological characters [38,39]. However, no method is universally accepted at present [40]. Our research combines the maximum ratio and the threshold methods for phenology data extraction [start of growth season (SOG), end of growth season (EOG), and length of growth season (LOG)]. The specific steps are as follows: first, the multi-year average of 10-day NDVI time series after smooth treatment is calculated to obtain the multi-year average annual change curve for each pixel. The NDVI difference between two adjoining points of each pixel (i.e. relative variation value) is calculated, and the NDVI threshold of SOG and EOG is determined using the maximum absolute value for relative change (Figure 2). A second type of data is obtained through HANTS (i.e. NDVI time series data with temporal resolution of one day) to determine the Julian days of SOG and EOG. When the NDVI value of some pixels is larger than the SOG threshold within a specific time period, the day is regarded as SOG. When NDVI is smaller than the EOG threshold, the day is regarded as EOG. The difference between EOG and SOG is considered as LOG.

(3) Analysis method. We fitted a linear regression trend to the annual alpine grassland SOG, EOG, and LOG using ordinary least squares. As SOG and EOG of some pixels are not valid in certain years due to the effect of various environmental factors, we only considered pixels in which the phenology of alpine grassland are available for all 11 years of the study period. To analyze the spatial change patterns of alpine grassland, the SOG, EOG, and LOG average values in different elevation zones and physico-geographical regions in the Qinghai-Tibetan Plateau were calculated, and the phenological change difference in the different elevation zones and physic-geographical regions was then analyzed.

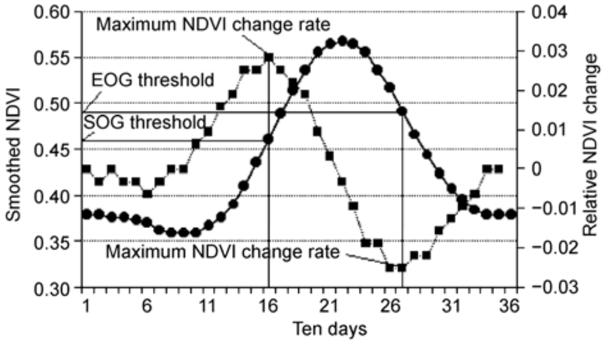

Figure 2 Definition of NDVI threshold of SOG and EOG according to NDVI change rate in the multi-year average NDVI seasonal cycle.

2 Result analysis

2.1 Spatial distribution patterns of multi-year average of phenology

The spatial distribution pattern of multi-year average of phenology of alpine grasslands in the Qinghai-Tibetan Plateau is shown in Figure 3. From southeast to northwest, SOG was gradually delayed, EOG gradually advanced, and LOG gradually shortened, which significantly manifest the regional differentiation regularity of climate and terrain. SOG mainly occurs in the 120th–170th day, but it arrives before the 120th day in low river-valley areas southeast of the plateau and appears after the 170th day in some high altitude or latitude areas, such as the source area of the Yangtze, Yellow, and Yarlung Zangbo Rivers. EOG primarily occurs between the 250th and 300th d and also displays difference in areas of different altitudes and latitudes. LOG is mainly between 90 and 130 d, but it is longer than 130 days in some eastern and southern areas.

The phenology of alpine grasslands in the Qinghai-Tibetan Plateau is closely related to altitude (Figure 4). Between 2500 and 5500 m, SOG is delayed by 9 d, EOG comes earlier by 1 d, and LOG is shortened by 9 d for every 1000 m rise in altitude. The Figure shows that the regularity of the change in phenology along with altitude is not obvious when the altitude is below 3500 m, which greatly fluctuated. In particular, EOG is delayed with the increase in altitude. However, the phenology changes significantly with the increase in altitude when the altitude is above 3500 m. The relationship between phenology and altitude when the altitude is below 3500 m could be related to human activities (such as land management and land use difference), resulting in an unclear relationship between phenology and altitude.

2.2 Analysis of inter-annual phonological change

(1) Inter-annual phonological change at the regional scale. The inter-annual phonological change characteristics of

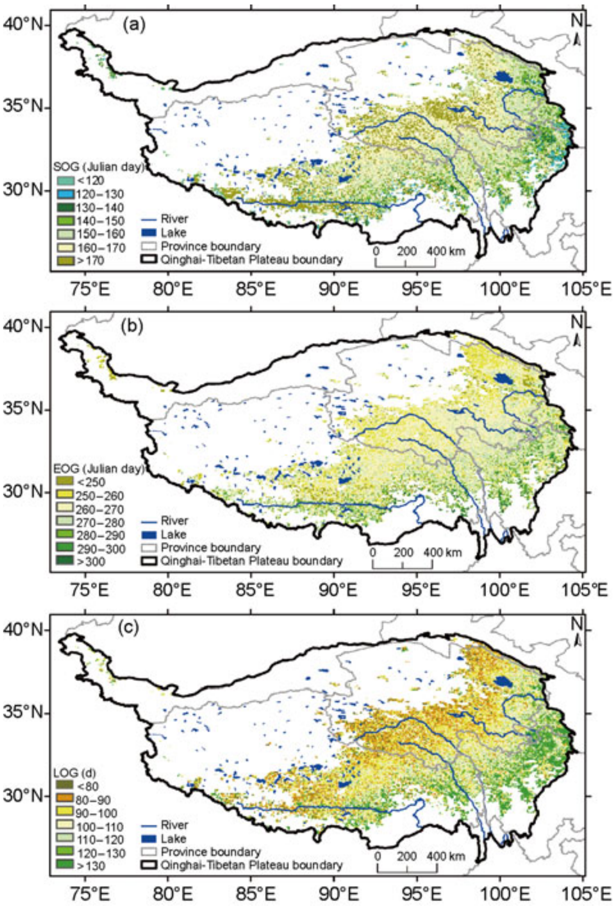

Figure 3 Average spatial distribution of the alpine grassland's SOG (a), EOG (b), and LOG (c) during 1999–2009 in the Qinghai-Tibetan Plateau.

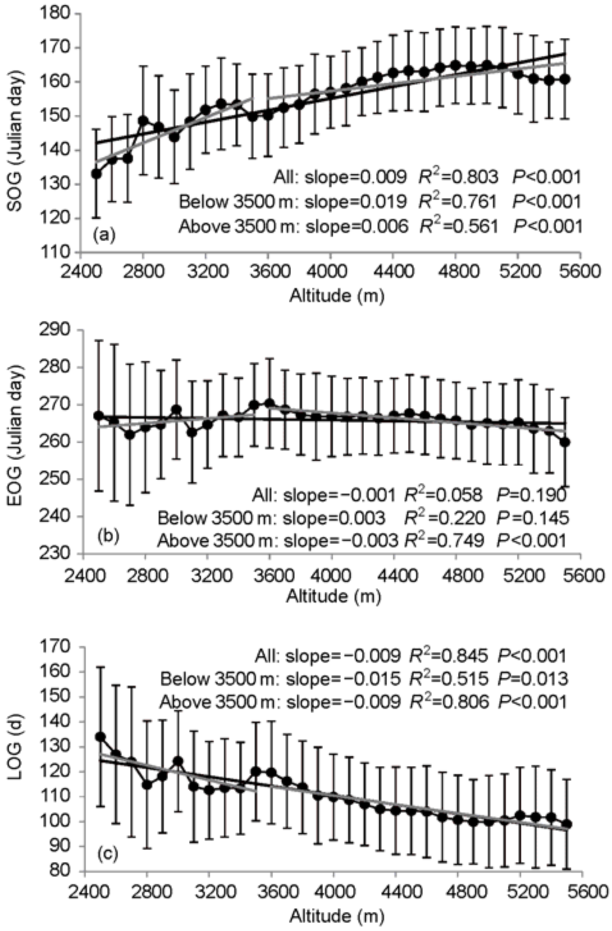

Figure 4 Changes in the mean of alpine grassland's SOG (a), EOG (b) and LOG (c) during 1999–2009 along altitude gradient in the Qinghai-Tibetan Plateau. Error bars show the standard deviation of the pixels in each elevation bin. Solid line shows regression of the entire elevation gradient. Dashed lines show the regression of elevation bins below and above 3500 m, respectively.

alpine grasslands in the Qinghai-Tibetan Plateau during 1999–2009 are shown in Figure 5. SOG came early, and the variation amplitude for every 10 years was six days (R^2= 0.281, P=0.093). Compared with SOG change in other areas in the 1980s and 1990s, the research result in this paper is obviously higher than 3 d/10 a [41] for the whole world, 3.3 d/10 a [34] in the Eurasian continent, and 3.1 d/10 a [42] in the northern hemisphere and is lower than 7.9 d/10 a [37] in China. Jeong et al. [42] discovered that the increase in amplitude in the northern hemisphere during 2000–2008 is 0.2 d/10 a, based on AVHRR data, and the results presented in this paper are larger than this value.

The inter-annual change trend of EOG was weak, and the variation amplitude every 10 years was approximately two days (R^2=0.031, P=0.605). Overall, EOG was delayed. Compared with the EOG changes in other areas in the 1980s and 1990s, the research result in this paper is higher than 0.5 d/10 a [41] for the whole world and lower than 6.1 d/10 a [34] in the Eurasian continent, 2.3 d/10 a [42] in the northern hemisphere, and 3.7 d/10 a [35] in China. The variation is also lower than 2.5 d/10 a (2000–2008) [42] in the northern hemisphere under a roughly identical temporal scale.

LOG showed a significant variation trend and increased generally. The variation amplitude for every 10 years was eight days (R^2=0.479, P=0.018). Compared with the LOG change in other areas in the 1980s and 1990s, the research result in this paper is higher than 3.8 d/10 a [41] for the entire world and 5.6 d/10 a in the northern hemisphere and is lower than 13.3 d/10 a [34] in the Eurasian continent and 11.6 d/10 a [37] in China. However, it is higher than 2.8 d/10 a (2000–2008) [42] in the northern hemisphere under a roughly identical temporal scale.

In general, the LOG change trend of alpine grasslands in the Qinghai-Tibetan Plateau is most obvious, followed by SOG and EOG in that order.

(2) Spatial distribution patterns of inter-annual phenological change. During 1999–2009, the inter-annual phonological change trend in alpine grasslands in the Qinghai-Tibetan Plateau displayed a large spatial difference (Figure 6). SOG came early in 91.73% of the area and was delayed in 8.27% of the area. Among them, the areas where SOG obviously advanced accounted for 41.26% (P<0.2). The variation amplitude increased gradually from west to east. In particular, some river-valley areas in the east and

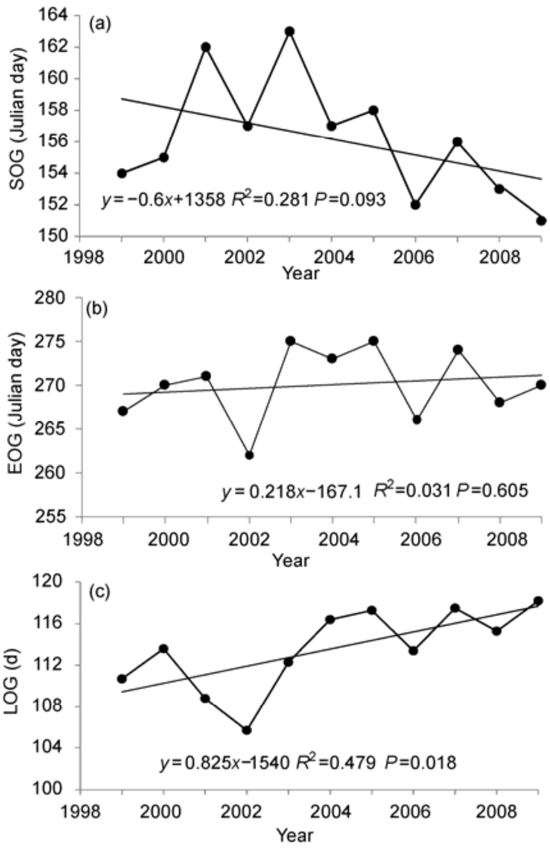

Figure 5 Inter-annual variation of alpine grassland's SOG (a), EOG (b), and LOG (c) from 1999 to 2009 in the Qinghai-Tibetan Plateau.

the south exhibited the largest variation amplitude. EOG arrived early in 76.92% of the area and was late in 23.08% of the area. The areas with obvious advance and delay account for approximately 13.27% and 23.02%, respectively (P<0.2). Figure 6(b) and (e) shows that most areas exhibit early EOG and a large variation amplitude, but the level of significance is low; late EOG are shown in few areas, but almost all areas have attained significant level and are mainly distributed in the east of the Plateau. Based on actual changes, LOG lengthens in approximately 46.25% of the area and is shortened in 53.75% of the area. The areas with obvious extension and shortening account for approximately 45.56% and 14.59%, respectively (P<0.2). LOG lengthening mainly occurs in the east of the Plateau, and LOG shortening appears in the west. Regarding the phenology of alpine grasslands in the Qinghai-Tibetan Plateau, the inter-annual change trend in the east is evidently stronger than that in the west.

(3) Phenological change trends in relation to elevation. The inter-annual phonological change of alpine grasslands in the Qinghai-Tibetan Plateau shows obvious differentiation along the altitude gradient. Figure 7 shows the relationship between the inter-annual change trend and the altitude gradient for every 100 m altitude zone during 1999–2009. Different altitude zones showed an advancement SOG trend. However, SOG was mainly delayed before 2003 and advanced again after 2003. In terms of variation amplitude and significance level, the advancement amplitude gradually decreased from 24 to 3 d/10 a with the rise in altitude, and the significance level also reduced gradually. The inter-annual change of EOG differs significantly, mainly showing an advancement trend before 2002 and a delay trend after 2002. In general, EOG was delayed in most high-altitude zones and only arrived early when the altitude is approximately 5000 m. In terms of variation amplitude and significance level, the delay amplitude gradually decreased from 13 d/10 a to zero with the rise in altitude, and the significance level also reduced gradually. LOG showed a shortening trend before 2002 and a lengthening trend after 2002. In terms of variation amplitude and significance level, the lengthening amplitude gradually decreased from 34 d/10 a to 2 d/10 a with the rise in altitude, and the significance level also reduced gradually. Piao et al. [17] drew the following conclusion from the analysis of AVHRR-NDVI data during 1982–2006: the SOG in the Qinghai-Tibetan Plateau showed a reversed change before and after 1999, particularly evident in high-altitude zones. Within the period analyzed in this paper (1999–2009), the inter-annual phonological change in low-altitude zones in the Qinghai-Tibetan Plateau was stronger than that in high-altitude zones (whether in terms of variation amplitude or significance level). No contradiction existed between the two conclusions. In high-altitude zones in this paper, SOG also showed a reversed change trend before and after 2003. The variation amplitude in low-altitude zones was small, but the change trend during the period was consistent (Figure 7(a)), resulting in the condition that the change trend and amplitude in low-altitude zones are obviously greater than those in high-altitude zones. Thus, the inter-annual phonological change in the growth season in high-altitude zones in the Qinghai-Tibetan Plateau is more complex than that in low-altitude zones.

(4) Phenological change trends in relation to physico-geographical regions. The inter-annual phonological changes of alpine grasslands in the Qinghai-Tibetan Plateau differ greatly in different physico-geographical regions. Figure 8 shows the inter-annual phonological change slope and significance level in different physico-geographical regions in the Qinghai-Tibetan Plateau during 1999–2009, which shows that SOG displayed an advancement trend in all physico-geographical regions; however, the advancement amplitude and significance level were different. The eastern Qinghai-Qilian montane steppe zone displayed the highest advancement amplitude and significance level, and the Southern Tibet montane shrub-steppe zone had the lowest advancement amplitude and significance level. EOG was generally late in each natural zone, with significant fluctuation and low significance level. LOG displayed an extension trend. In addition, the eastern Qinghai-Qilian montane steppe zone exhibited the largest extension amplitude of the growth season and the highest significance level. However,

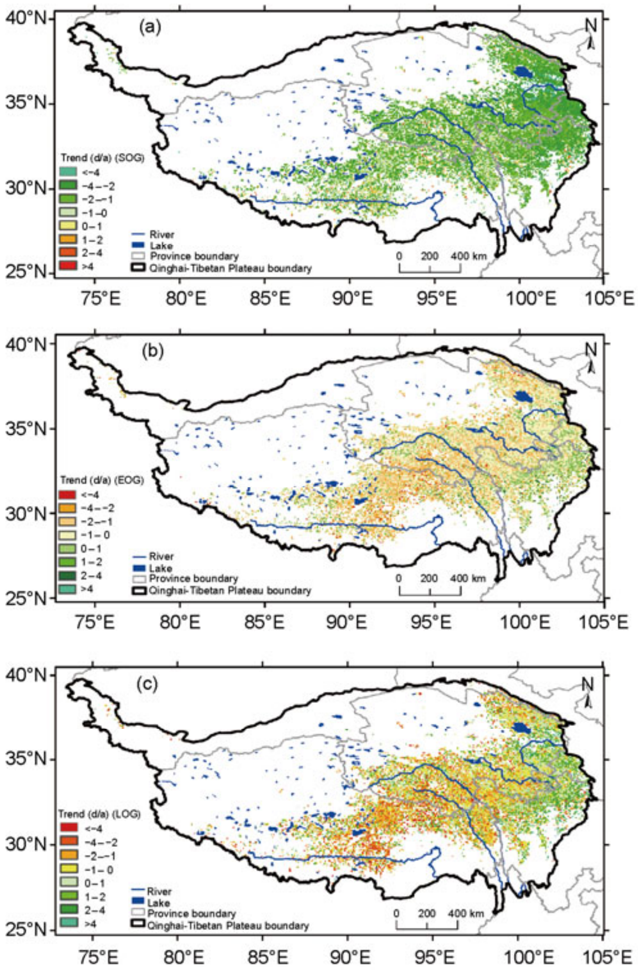

Figure 6 Spatial distribution of inter-annual change trend and significance of alpine grassland's SOG, EOG, and LOG from 1999 to 2009 in the Qinghai-Tibetan Plateau. (a) and (d) The trend and significance of SOG; (b) and (e) the trend and significance of EOG; (c) and (f) the trend and significance of LOG.

the Southern Tibet montane shrub-steppe zone had the smallest extension amplitude and the lowest significance level. Overall, the inter-annual phonological change trend of the growth season weakened gradually from east to west.

3 Discussion

Many studies have so far employed various remote sensing data to analyze plant phenology in the northern hemisphere. Analysis based on AVHRR data established that SOG in the northern hemisphere showed an advancement trend in the 1980s and 1990s but later demonstrated a delayed trend [17–19,44]. However, MODIS data analysis indicates that SOG still retained an advancement trend during 2000–2010. Regarding autumn phenology, AVHRR and MODIS data analyses showed a delayed trend of EOG from 2000 to 2010. However, no obvious EOG change trend was shown before 1999, based on the AVHRR data analysis [44]. Shen [45] analyzed the SOG change characteristics of the meadow and steppe in the Qinghai-Tibetan Plateau during 1998–2008 using MODIS data and drew the following conclusion: The SOG of grassland in the Qinghai-Tibetan Plateau showed a delay trend during 1998–2003 and an advancement trend during 2003–2008. However, the advancement trend prevailed during 1998–2008, consistent with the trend obtained from the current study. With regard to variation amplitude, previous research showed that the advancement amplitude of SOG is 0.2–8 d/10 a, the delay amplitude of EOG is 0.5–6.1 d/10 a, and the extension amplitude of LOG is 0.6–14 d/10 a [41]. However, the values of these three parameters in this paper are 6, 2, and 8 d/10 a, respectively, basically within the range of variation amplitude determined from previous studies. The phenological change amplitude from different studies varied, which could be related to different data sources and temporal scales [46].

With respect to data sources, current phonological research mainly adopts AVHRR, MODIS, and SPOT data. Different data could lead to different results because of the following reasons: (1) The three types of data have different infrared and near-infrared bandwidths used in NDVI calculation. The bandwidths based on MODIS are 620–670 nm

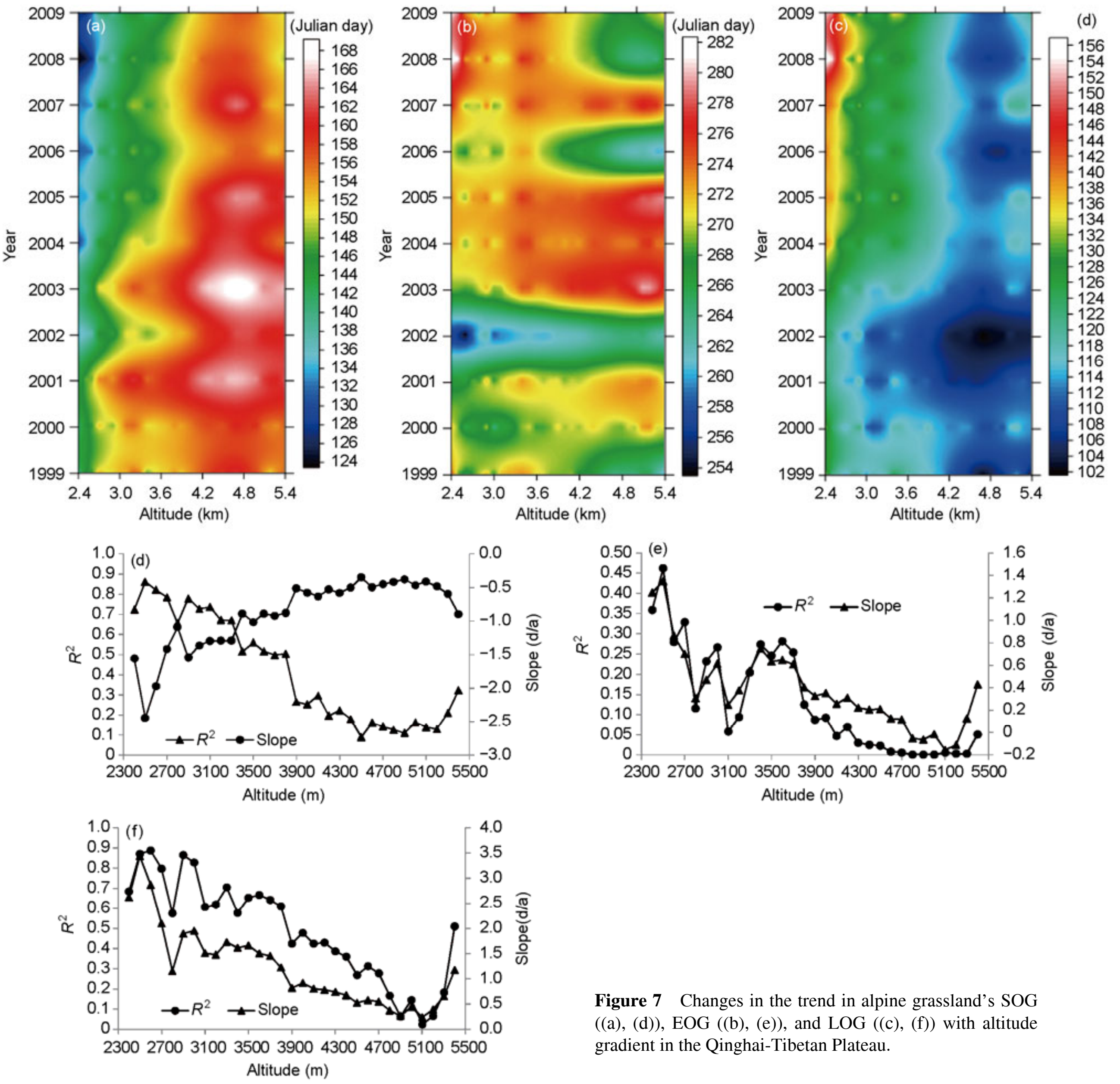

Figure 7 Changes in the trend in alpine grassland's SOG ((a), (d)), EOG ((b), (e)), and LOG ((c), (f)) with altitude gradient in the Qinghai-Tibetan Plateau.

and 841–876 nm, respectively; those based on SPOT are 610–680 nm and 780–890 nm, respectively, and the bandwidths based on AVHRR are 585–680 nm and 730–980 nm, respectively. Compared with AVHRR, the bandwidths of MODIS and SPOT are narrower. (2) The AVHRR data series totally adopts four types of sensor (NOAA-14, NOAA-16, NOAA-17, NOAA-18) [47]. Although mutual correction was conducted on the different sensors, certain data errors still exist. (3) Compared with AVHRR, the sensors of MODIS and SPOT are modified greatly, such as geometric and radiometric calibration. (4) The spatial resolutions of MODIS (250 m, 500 m, and 1 km) and SPOT (1 km) are higher than that of AVHRR (8 km). (5) In terms of atmospheric correction, sub-pixel cloud pollution and water vapor influence are considered in the AHVRR data, which involve the influence of volcanic aerosol. The MODIS and SPOT data not only correct the scattering of molecules and aerosol in the atmosphere but also consider the absorption of gases (MODIS mainly considers ozone absorption, but SPOT considers absorption of ozone, water vapor, and other gases). AVHRR and SPOT adopt the maximum-value composition (MVC), but the MODIS data adopt the constrained-view angle-maximum value composite. Fontana et al. [48] analyzed the phenology of alpine grasslands using AVHRR, SPOT, and MODIS and opined that the MODIS and SPOT data are superior to AVHRR data. However, many uncertainties exist in remote sensing phenology because it is highly dependent on the quality of satellite data. In addition, no comprehensive understanding has been established on how remote sensing phenology is related to

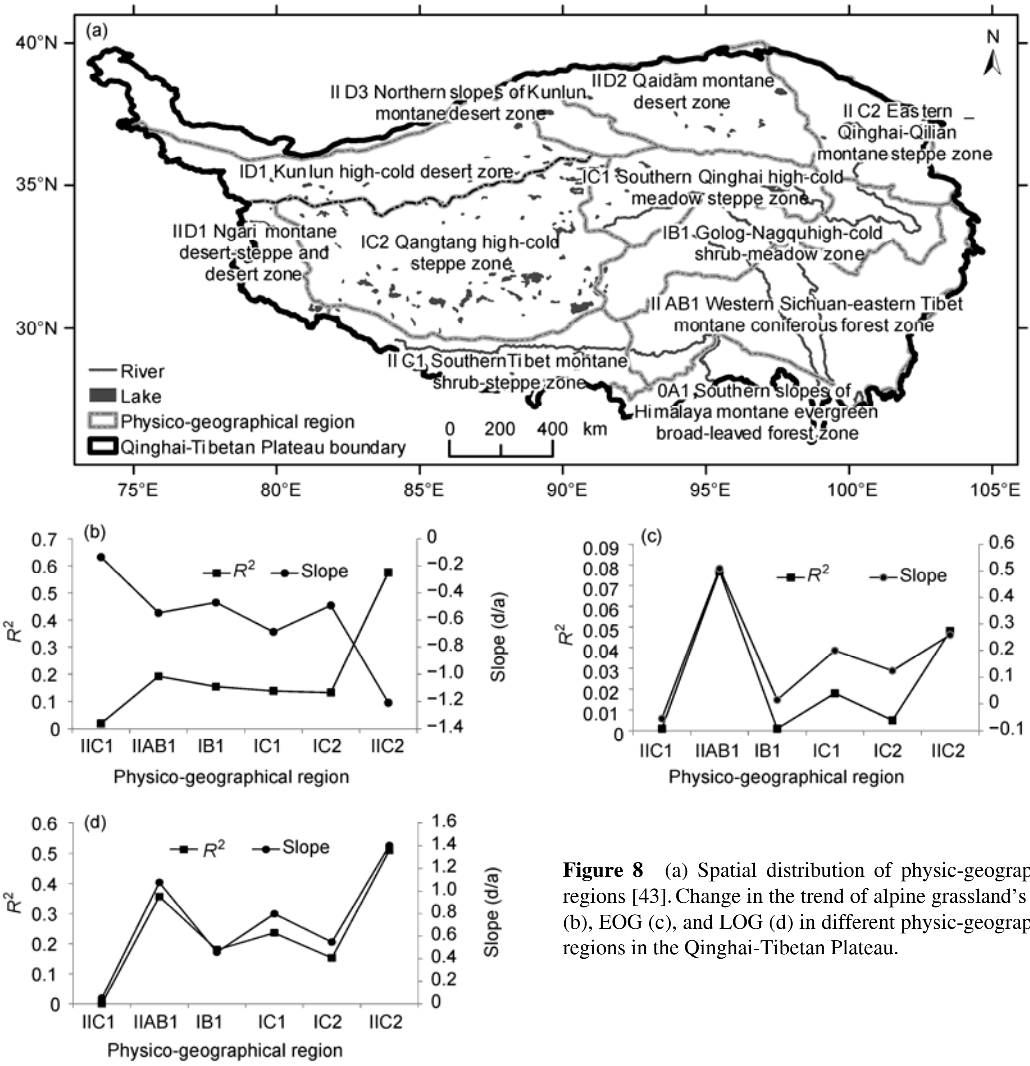

Figure 8 (a) Spatial distribution of physic-geographical regions [43]. Change in the trend of alpine grassland's SOG (b), EOG (c), and LOG (d) in different physic-geographical regions in the Qinghai-Tibetan Plateau.

ground-based phenology because of lack of *in situ* observation. Therefore, spatially and temporally explicit historical data sets from both satellite and in situ observations are certainly required to validate and correct the results in future plant-phenology studies.

The temporal scale of most previous studies was extended only up to 2006. The SOG and EOG extracted from AVHRR and SPOT data are compared and analyzed in Figure 9, which shows that SOG extracted from AVHRR data is lower than that extracted from SPOT, but EOG is consistent. SOG showed an obvious advancement trend before 1998 and a delay trend during 1998–2003. It also showed an advancement trend after 2003. When only the data before 2006 are considered, the change trend based on AVHRR and SPOT data is consistent, but different results appear after the temporal scale is extended. Analysis based on both types of data sources indicates a weak delay trend of EOG. For previous studies that found that SOG was delayed after 1999 [17,18], many controversial topics exist, mainly focusing on the reasons of the phenology delay. Yu et al. [18] believed that the phenology delay appeared to be related to later fulfillment of chilling requirements, and winter warming could strengthen this effect or even reverse the advancing trend of the spring phenology. Chen et al. [49] believed that, on the regional scale, the possible delayed spring phenology in the meadow and steppe should be attributed not only to winter and spring warming but also to grassland degradation, thawing-freezing process, and their combined effects. Yi and Zhou [50] believed that changes in contamination played an important role in the retrieval of NDVI, resulting in phenology delay. The current paper suggests that such delay is closely related to the difference in the analyzed temporal scale because the time series leading to such conclusion is in 1999–2006. However, data analysis based on SPOT (1999–2009) and MODIS (2000–2010) indicates that SOG was delayed and then advanced after 1999, but the overall change trend was not delayed, and an advancement trend appeared. Thus, although AVHRR data are considered as an important data source in evaluating the phonological change from 1981 up to the present, SPOT VGT and MODIS data have been an important supplement to phenological change studies in the last 10 years.

The extension of the growth season, especially the advancement of spring phenophase, is considered as one of the main factors that enhanced the carbon sink function in middle-high altitude areas of the northern hemisphere during 1980–2000 [9,51]. The extension of the growth season in alpine grasslands in the Qinghai-Tibetan Plateau can enhance carbon sink function, reduce CO_2 accumulation in atmosphere, and decrease climate-warming rate; however, the effect of changes in the growth season duration on carbon balance is not clear at present and needs further study. In addition, changes in growth season duration will inevitably significantly affect animal-husbandry production in the Qinghai-Tibetan Plateau, irrespective if SOG arrives in advance or EOG is delayed. The extension of growth season will lead to extension of grazing activities, resulting in various effects on the ecosystem of alpine grasslands, which requires further study.

4 Conclusions

The multi-year average phenophase distribution of alpine grasslands in the Qinghai-Tibetan Plateau is closely related to hydrothermal conditions. With the worsening in hydrothermal conditions and rise in terrain from southeast to northwest, SOG delay, EOG advancement, and LOG shortening appear gradually. Altitude plays a significant role in regional differentiation of phenology. However, a dividing line (3500 m) exists in the Qinghai-Tibetan Plateau. The relationship between altitude and phenology is not obvious below the line but is evident above this line.

For alpine grasslands in the Qinghai-Tibetan Plateau during 1999–2009, SOG generally exhibited an advancement trend, with variation amplitude of 6 d/10 a (R^2=0.281, P=0.093). EOG showed a delay trend, with variation amplitude of 2 d/10 a (R^2=0.031, P=0.605), and LOG underwent a lengthening trend, with variation amplitude of 8 d/10 a (R^2=0.479, P=0.018). However, the spatial difference was large. The areas that featured SOG advancement, EOG delay, and LOG extension were mainly distributed in the east of the Plateau, whereas the areas that feature SOG delay, EOG advancement, and LOG shortening were mainly distributed in the middle and western parts of the Plateau. Most areas in the Plateau experienced evident SOG advancement, especially east of the Plateau where advancement was most obvious.

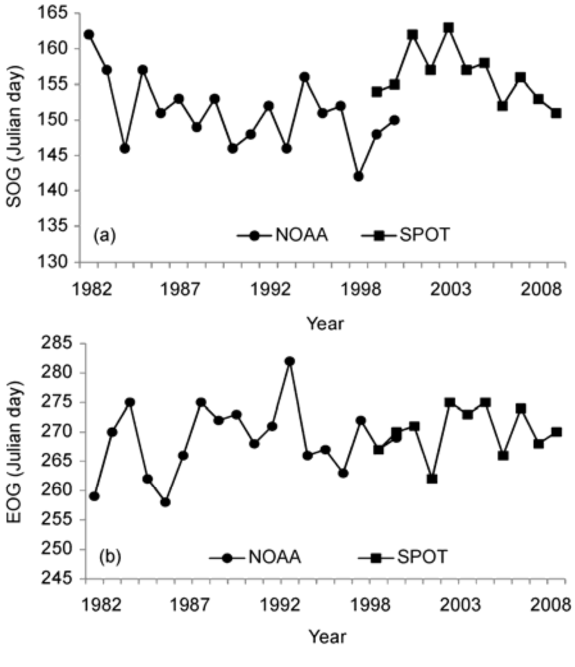

Figure 9 Inter-annual variation of alpine grassland's SOG (a) and EOG (b) from 1982 to 2009 in the Qinghai-Tibetan Plateau.

The inter-annual phonological changes of alpine grasslands in the Qinghai-Tibetan Plateau vary greatly with different altitudes and natural zones. In terms of altitude, the inter-annual phonological changes of the growth season in high-altitude zones are more complex than those in low-altitude zones. With regard to natural zones, the eastern Qinghai-Qilian montane steppe zone shows the highest variation amplitude and significance level. However, the Southern Tibet montane shrub-steppe zone has the lowest variation amplitude and significance level.

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