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Spatial and temporal variation of vegetation phenology and its response to climate changes in Qaidam Basin from 2000 to 2015

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Abstract: Based on TIMESAT 3.2 platform, MODIS NDVI data (2000–2015) of Qaidam Basin are fitted, and three main phenological parameters are extracted with the method of dynamic threshold, including the start of growth season (SGS), the end of growth season (EGS) and the length of growth season (LGS). The spatial and temporal variation of vegetation phenology and its response to climate changes are analyzed respectively. The conclusions are as follows: (1) SGS is mainly delayed as a whole. Areas delayed are more than the advanced in EGS, and EGS is a little delayed as a whole. LGS is generally shortened. (2) With the altitude rising, SGS is delayed, EGS is advanced, and LGS is shortened and phenophase appears a big variation below 3000 m and above 5000 m. (3) From 2000 to 2015, the temperature appears a slight increase along with a big fluctuation, and the precipitation increases evidently. (4) Response of phenophase to precipitation is not obvious in the low elevation humid regions, where SGS arrives early and EGS delays; while, in the upper part of the mountain regions, SGS delays and EGS advances with temperature rising, SGS arrives early and EGS delays with precipitation increasing.

Keywords: Qaidam Basin; climate changes; remote sensing phenology; time series reconstruction

1 Introduction

Phenology is a subject to study various seasonal phenomena in biological populations and the relationship between phenology and environmental periodic changes (such as climate, hydrology and soil, etc.) (Lieth *et al*., 1974; Zhu *et al*., 1999). As a research object of phenology, phenological phenomena, especially the interannual variations of start of growth season (SGS), end of growth season (EGS) and length of growth season (LGS), reflect the changes of climate, hydrology and soil for a period of time. So many scholars figuratively speak that phenology is the most sensitive comprehensive indicator of seasonal and interan-

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nual variation of climate and environment. Phenological changes directly affect biological production and have a critical role in ecosystem productivity and carbon cycling. There are many characteristics in the use of remote sensing means to monitor phenology, such as multi-phases, covering a wide, continuous space, long-time series, being able to quantitatively reflect the seasonal growth and development of plants and its interannual changes and so on (Reed *et al*., 1994; Mouslin *et al*., 1997; Schwartz, 1998; Chen *et al*., 2005). As more and more experts and scholars use remote sensing technology on vegetation phenology change research in depth, it has gradually developed into an independent discipline and has become a frontier for global climate change and terrestrial ecosystem dynamics research (Chen *et al*., 2009).

Good hydrothermal conditions provide reliable protection for plant growth and development. Chmielewski *et al*. (2001) found that SGS occurred 7 d in advance at every 1°C rise in spring temperature in Europe. Through the study of more than 20 species of vegetation phenology in Germany, Menzel *et al*. (2003) found that when the temperature rose by 1°C, the flowering and leaf expansion of spring plants occurred 2.5–6.7 d in advance. Zheng *et al*. (2002) analyzed the effects of climate warming on the phenological changes of vegetation in China in recent 40 years by collecting 26 observation sites, and found that when China's spring temperatures rose 0.5°C, SGS had an average of 2 d in advance in the 1980s. Ma *et al*. (2012) studied the phenology of vegetation in China by means of ground observation, remote sensing monitoring and model simulation. The results showed that China's temperature rises every 1°C, the spring phenophase would be ahead of 4.93 d in the past 30 years. In addition to the temperature, the impact of precipitation on vegetation phenology should not be ignored. When drought occurs, even the photothermal conditions are sufficient but cannot meet the needs of plant growth, the moisture has become a major factor affecting the growth and development of vegetation. In the study of phenology-climatic relationships in four areas of the Qinghai Plateau, Li *et al*. (2010) believed that annual precipitation and stage precipitation had some influence on the critical period of vegetation phenology growth, especially SGS postponement may be caused by accelerated evaporation of water at elevated temperatures, which emphasized the importance of moisture. In the study of phenology-climatic relationships in the Qinghai-Tibet Plateau, Ding *et al*. (2012) found that SGS was negatively correlated with precipitation. Song *et al*. (2012) studied the relations between phenological changes of four typical vegetation types and climate in the Tibetan Plateau. The results showed that the precipitation in the previous year had a great influence on the SGS of alpine shrub meadow, and its influence degree was higher than that in spring temperature.

Qinghai-Tibet Plateau is the most sensitive area of response to the global climate change, its hydrothermal condition is at the limit of biological growth and the ecosystem is extremely fragile (Yao *et al*., 2006). As the highest elevation basin in the world, Qaidam Basin is located in the northeastern part of the Qinghai-Tibet Plateau. It is a transitional zone between the Qinghai-Tibet Plateau and the inland arid and semi-arid regions. Desert, oasis and alpine grassland are distributed inside it, forming a strong contrast, so that Qaidam Basin has become a unique geographical unit. In the past 30 years, the trend of increasing temperature and precipitation in Qaidam Basin has been stronger than that in the hinterland of the Qinghai-Tibet Plateau (Li *et al*., 2010; Han *et al*., 2001). Due to its significant ecosystem vulnerability and interannual volatility of climatic factors, Qaidam Basin is an ideal area for studying vegetation phenology and its response to climate change.

At present, there are few studies on phenology related to Qaidam Basin, but many researches on the Qinghai-Tibet Plateau. The area of Qaidam Basin is about 1/10 of the total Qinghai-Tibet Plateau, and it is difficult to express the details of the phenological changes in Qaidam Basin under such a scale difference. The study of remote sensing phenology of the Qinghai-Tibet Plateau, some are regional differences study based on pixel scale, rarely explore its climate-driven mechanism (Ding *et al*., 2012). Involving the relationship between phenology and climate, the study often only selected some typical sample sites, can not capture the changes in the regional space (Li *et al*., 2010). With the deepening of research and the progress of related technologies, it is necessary to improve precision to the pixel scale and to carry out the study on dynamic relationship between phenology and climate in Qaidam Basin.

2 General situation of the study area

Qaidam Basin is located in the northeastern part of the Qinghai-Tibet Plateau, and is an approximately triangular, closed plateau mountain tectonic basin (Figure 1). The northeastern, northwestern and southern edges of the basin are surrounded by Qilian Mountains, Altun Mountains and Kunlun Mountains respectively. The inner elevation of the basin is between 2652 m and 3350 m. If the outer mountain range are covered, it can reach 6066 m. From the edge of the basin to the center, the geomorphic types are mountain, gobi, fixed and semi-fixed sand dune and wind erosion hill, alluvial-proluvial plain, and lacustrine plain (Lu *et al*., 2015). There are lakes in the basin in decentralized distribution, dotted with multi-center circular zonary terrains. The Qaidam Basin is located in the transitional zone between the Qinghai-Tibet Plateau and the arid area of northwest China, which is less in precipitation and high in evaporation, a typical continental climate. The arid and alpine natural conditions make Qaidam Basin both salty desert landscapes and the attributes of the Qinghai-Tibet Plateau (Zhang *et al*., 1988). The vegetation is sparse in the basin center, where there are mainly salt lakes and deserts, accounting for 53.68% of the whole basin area. The dense vegetation area mainly lies in inland rivers, lakes and alluvial and diluvium deposits originated from the former formed by the melted ice and snow from the surrounding

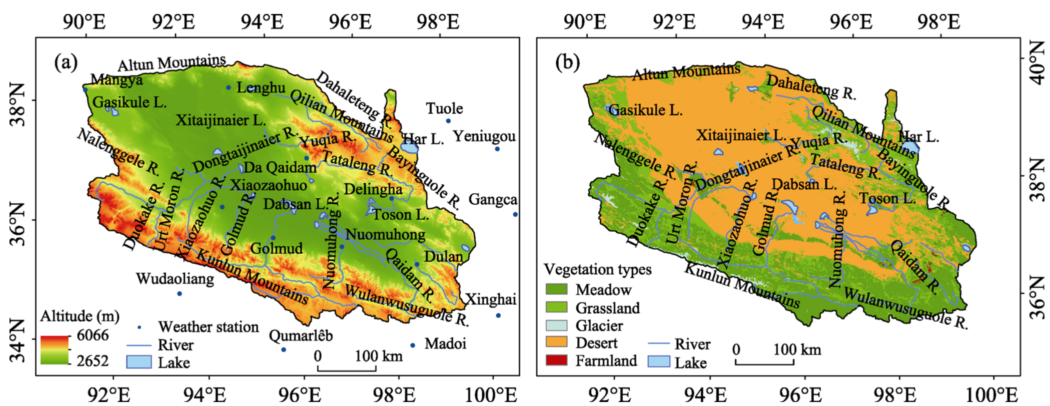

Figure 1 Location of Qaidam Basin and vegetation distribution

mountains (Ma *et al*., 2008). There is a certain amount of alpine meadow in the upper part of the mountain and gentle slope. Farmland is mainly distributed in alluvial and diluvium fan of the basin center.

3 Data and methods

3.1 Data sources and pretreatment

According to the characteristics of the arid and semi-arid climate and vegetation growth in Qaidam Basin, this study was given dual requirements in terms of spatial and temporal accuracy of the data source. In the end, we selected the MODIS NDVI dataset provided by the CAS data center (http://www.gscloud.cn/), with a time range of 2000–2015, spatial resolution of 500 m, temporal resolution of 5d, and a total of 1152 periods.

Meteorological data is derived from the National Meteorological Science Data Sharing Service Platform (http://data.cma.cn/). Daily temperature and precipitation data from 2000 to 2015 were collected from 18 meteorological stations in Qaidam Basin and its surroundings. The daily temperature and precipitation were treated respectively as the 5 d mean or 5 d sum. With separate interpolation, the climate raster images were obtained with the same spatial and temporal resolution as the phenological data. The specific approach was as follows: Temperature interpolation method: first, the temperature data were corrected to the elevation of 0 m, and then were interpolated with the Kriging method. Finally, the DEM data of Qaidam Basin were used for altitude correction. Method of precipitation interpolation: Kriging method was used to interpolate directly.

3.2 Reconstruction of time series and extraction of phenological parameters

Three parameters of vegetation, the start of growth season (SGS), the end of growth season (EGS) and the length of growth season (LGS) were used to reflect the phenological changes of vegetation. SGS, which is based on remote sensing technology, refers to the date when most plants in the community begin to expand leaves and grow normally. After this date, vegetation enters the rapid growth stage. EGS refers to the date in which the majority of plants in the community can not grow normally and the leaves begin to turn yellow, after which the vegetation enters the stage of death or dormancy. LGS equals EGS minus SGS, which is different from the traditional growth season concept “the number of days a plant can grow in a year”. The results of remote sensing estimation are based on the phenological

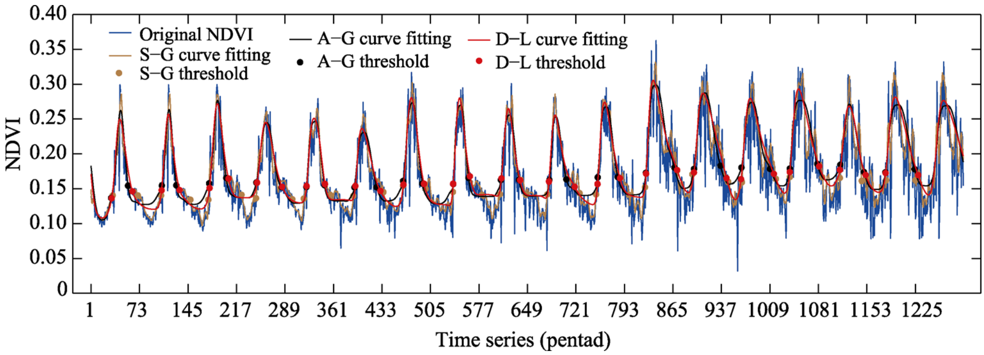

Figure 2 Comparison of three time series method for reconstructing a high-quality NDVI time series data

status of vegetation in a community or region. The results have a certain difference from those of traditional phenology, but the correlation is very high (Zhang *et al*., 2003).

This study is based on the development and improvement of the TIMESAT 3.2 platform by Jönsson and Eklundh (2015), which provides three time series reconstruction methods: Asymmetric Gaussians function fitting method (A-G) (Jönsson *et al*., 2002), Double Logistic function fitting method (D-L) (Fisher *et al*., 2006) and Savizky-Glolay filter algorithm (S-G) (Savitzky *et al*., 1964; Chen *et al*., 2004). The above algorithms are compared by extracting several typical vegetation types in Qaidam Basin. The results show that S-G algorithm is best fit for the details of the original NDVI curve. But at the same time, a lot of noise will be retained. The determination of phenological thresholds is subject to strong interferences. In view of this feature of S-G algorithm, the advantages may be apparent when the forest time series with higher vegetation indices are fitted. A-G algorithm has a high degree of coincidence when fitting the growth season curve and the envelope line, but in some cases, it is easy for the curve to produce mutations affected by the NDVI noise. It is difficult to capture the real growth of vegetation, so it is not suitable for the fitting of vegetation index in arid and semiarid areas. A-G algorithm can further reduce the larger noise in MODIS NDVI time series of Qaidam Basin and more smoothly reflect the growth of vegetation. Combined with previous studies and experiments in this study area, it is decided that A-G algorithm is used as a fitting method for the NDVI time series of Qaidam Basin.

For threshold settings, in a multi-regional study, Jönsson (2002) suggested setting the SGS and EGS thresholds to 20% of the NDVI amplitude in a year. Song *et al*. (2012) and Ma *et al*. (2016) studied the phenology of Northern Tibet and Qinghai-Tibet Plateau, respectively, using 0.1 for SGS threshold and 0.2 for EGS. Ma *et al*. (2014) believed that the threshold of 0.2 has a stronger consistency with the ground data after he compared 0.15, 0.2 and 0.25 to study the vegetation in Central Asia and Xinjiang arid area. Combined with the ground observation data of Qaidam Basin, and on the basis of a large number of experiments, it is found out that when the threshold was 0.2, the phenology was closer to local ground observation phenology. So, the threshold of 0.2 for SGS and LGS was determined in this study. The LGS will be obtained through the operations between SGS and EGS.

3.3 Statistical analysis method

(1) Trend analysis (Xu *et al*., 2013). In order to obtain the spatial and temporal characteristics of both vegetation phenology and climatic factors in Qaidam Basin, respectively, the trend analysis method was used to fit the interannual variation of both phenology and climatic factors from 2000 to 2015 in this study. And the statistical test method was used to test the changing trend.

(2) Partial correlation analysis (Zhang *et al*., 2011). The influences both of temperature and precipitation on phenological changes were investigated with the partial correlation analysis of pixels. First, the linear correlation coefficient between the phenology, temperature and precipitation was calculated (Yin *et al*., 2016). And then the partial correlation coefficient was calculated. Finally, the T-test was used to test the significance of the partial correlation coefficient.

4 Result analysis

4.1 The spatial and temporal pattern of plant phenology in Qaidam Basin

The spatial characteristics of multi-year average plant phenology in Qaidam Basin are calculated by raster processing, shown in Figure 3. Except deserts and bare rocks from the basin center to the northwest, multi-year SGS in the basin is between 130th and 170th d (Figure 3a). From the mid-east to the west, as well as to the edge of north and south, SGS is delayed gradually and the mean is 156th d as a whole. In a tiny part of the area, approximately accounted for 4% of the vegetation cover, SGS comes as early as 140th d, with its distribution in the small intermontane basin in the northeast of Qaidam Basin and the core area of the Oasis in the leading edge of alluvial and diluvial fan (Dulan-Nuomuhong-Golmud-Urt Moron) from the east to the center. The area with the value ranging from 140th d to 160th d is concentrated in the eastern low mountainous area and basin edge interval, which accounts for 56% of vegetation area. For the northern and southern edge with a high elevation in the mountainous area of Qaidam Basin and the central and southern edge in alluvial-proluvial fan apart from the core area of the Oasis, SGS is delayed over 160th d. In the aspect of interannual variation, the SGS of the vegetation in Qaidam Basin is delayed by 0.36 d/16 a as a whole. SGS in 67.9% of the vegetation area is delayed. The area where SGS advances significantly (P<0.01 and 0.01≥P<0.05) accounts for 5.6%, and 1.2% of the area is delayed

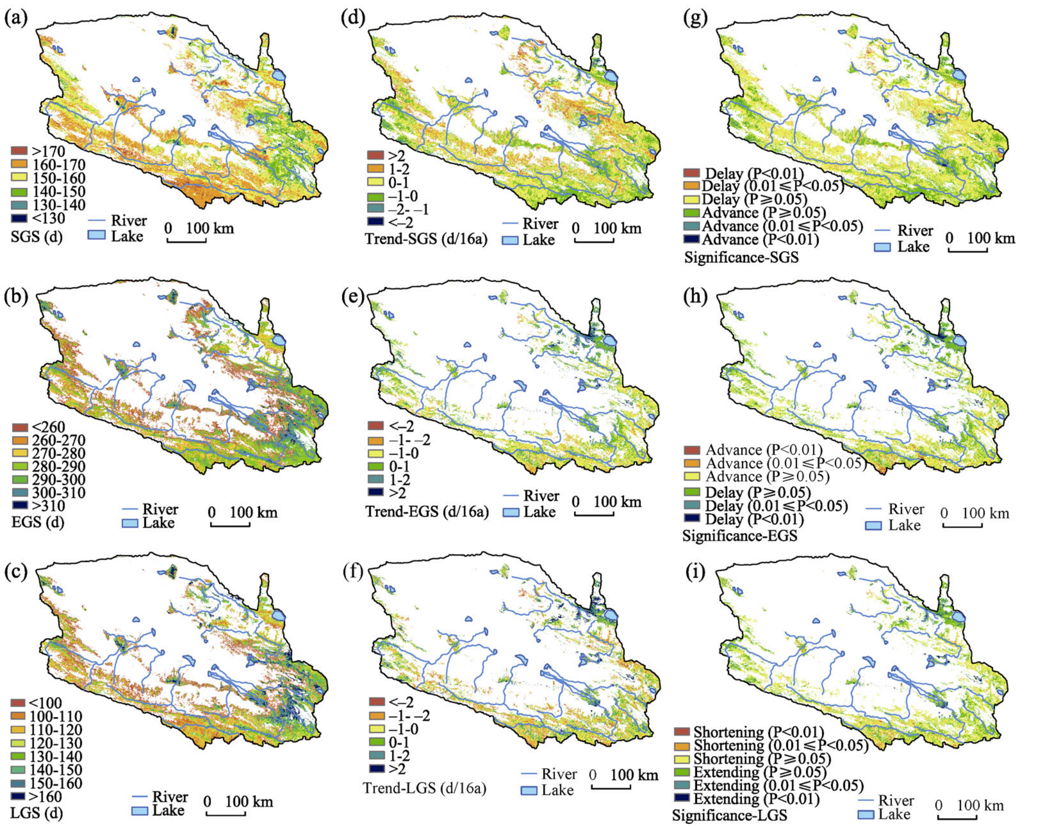

Figure 3 The spatial pattern (a–c) and interannual variation (d–i) of phenology in Qaidam Basin during 2000–2015

over 2 d, with its main distribution in the high-elevation region of Qilian Mountains and Kunlun Mountains locating in the northern and southern edges of the basin. The area with SGS advance accounts for 32.1% (Figures 3d and 3g). It is mainly distributed in the eastern mountain interval, the front of alluvial-proluvial fan in the central area, the northern slope of Qilian Mountains and both ends of southern slope of Kunlun Mountains, in which the area with significant SGS advance (P<0.01 and 0.01⩾P< 0.05) accounts for 1.6%, and 0.5% of the region advances more than 2 d , such as the northern slope of Qilian Mountains from Har Lake to the Da Haleteng River and the mountain valley of the upper Xiangride River.

EGS mainly occurs on 270th–310th d, with the mean being 294th d (Figure 3b). In the eastern low mountains, the oasis in the front of alluvial-proluvial fan and the mountain interval valley in northern and southern sides of the basin, EGS is late than 300th d, which appears after October. Other areas accounting for 47.7% of vegetation coverage show a vertical differentiation law consistent with SGS. That is, EGS is delayed with the increase of elevation (Figures 3e and 3h). The EGS of the vegetation in the basin is delayed by 0.04 d/16 a as a whole. EGS is delayed in 13.9% of the area, which is mainly distributed in the front of alluvial and diluvium fan in the basin center, the eastern low mountainous area, the northern slope of Qilian Mountains and the intervale of Kunlun Mountains. The area where SGS is delayed accounts for 52.3%. But only in 9.7% of the area, SGS advances significantly, which is distributed in the eastern edge of Qaidam Basin and the southern slope of Kunlun Mountains.

Under the interaction of SGS and EGS, LGS mainly concentrates in 120 d–170 d, with the average being 138 d (Figure 3c). The area where LGS is longer than 150 d includes the west bank of Gaskule Lake, east bank of Sugan Lake, some small basins in mountains lying in the east of Qaidam Basin and the front of alluvial-proluvial fan in the basin center, and is covered by 24.2% of the vegetation. The area where LGS is shorter than 130 d accounts for 35.7% lies in the southern slope of Kunlun Mountains and the mountains around Hela Lake of Qilian Mountains. The area where LGS is among 130 d–150 d is widely distributed in the regions between 150 d and 130 d, such as valleys, floodplains, lacustrine plains, the river downstream in alluvial- proluvial fan and slow slopes. The changing range of LGS is very large, from 2000 to 2015 (Figures 3f and 3i). It is shown that a shortening trend appears in 53.2% of vegetation area and only 4.1% of the area shows s significantly shortening tendency (P<0.01 and 0.01⩾P<0.05). On the contrary, the area where LGS is extended accounts for 46.8% of the vegetation area and the significantly extended area reaches to 6.3%, whose extended amplitude is over 2 d/16 a. Among it, the area where LGS is lower than 130 d mainly locates in Har Lake downstream of the north of Qilian Mountains, with its extended trend being obvious.

All the analysis shows that phenology of Qaidam Basin is influenced greatly by topography, so that the spatial and temporal variation of plant phenology presents the characteristic of gradient distribution from low to high altitude above sea level. Relational analysis between plant phenology and elevation in Qaidam Basin is made as follows.

4.2 The altitude distribution of plant phenology

With a line fit between the elevation data and the plant phenology in a unit of 100 m, the variation features of multi-year average of plant phenology is obtained during 2000 to 2015 in Qaidam Basin along the altitude gradient. Phenology presents significant spatial heterogeneity and altitude dependence along with the altitude rising (Figure 4). Specifically, at an altitude from 2600 m to 3000 m, SGS fluctuates from 149th d to 159th d, which mainly locates in the ecotone from oasis to mountain or agricultural planting area. Starting from 3000 m, phenology shows a regular delayed trend. SGS reached 164th d at 5200 m. Interannual variability analysis of SGS at different altitudes shows that vegetation turn green in advance below 3000 m and above 4800 m, and the area between 3000 m and 4800 m is delayed. The delay rate reached 1.15 d/16 a at 3400 m. This confirms the conclusion that the SGS delayed area in the previous study is larger than the advance region.

With 3300 m as a boundary, EGS shows two different trends: (1) Between 2600 m and 3300 m, EGS has a slightly fluctuating state from advance to delay. (2) Above 3300 m, EGS tends to advance from 306th d to 275th d, and the trend is faster and faster, reaching 3.96 d/16 a at 5300 m. For the interannual variation, the EGS is delayed below 4000 m and advance above it.

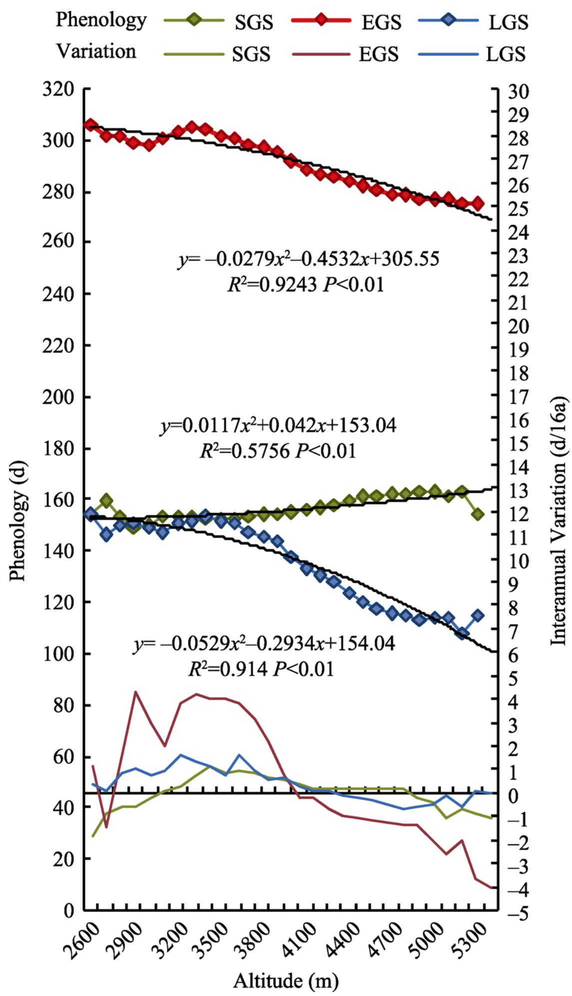

Figure 4 The relations between phenology and altitude of Qaidam Basin during 2000–2015

For LGS, 3500 m as a node, the fluctuation range of phenophase is 146 d to 154 d below 3500 m. Starting from 3500 m, LGS is from 153 d to 108 d or shorter. In terms of interannual variation, LGS performs an extension trend below 4300 m, and above 4300 m it is shortened.

To sum up, plant phenology is closely related to elevation in Qaidam Basin. Generally, SGS is delayed, EGS advances, and LGS is shortened along with altitude rise. And the elevation is mainly through the difference of hydrothermal composition and other environmental factors at different altitude to impact phenology. Among them, changes in the climatic factors that occur with elevation are important reasons for phenological changes.

4.3 Response of plant phenology to major climatic factors

4.3.1 Variation characteristics of temperature and precipitation in Qaidam Basin

The spatial and temporal distribution of temperature and precipitation from 2000 to 2015 is obtained by interpolation processing of 18 meteorological stations inside and around Qaidam Basin (Figure 5). The result shows that the multi-year average temperature (2000–2015) is 1.58°C in the Basin (Figure 5a). It is shown that the temperature rose significantly in Qaidam Basin at the beginning of the new century. Even the average temperature reached 3.45°C in 2004, and then declined for four consecutive years until it dropped to 0.29°C in 2008. From the beginning of 2009, temperature fluctuated around the average. By excluding the impact of the three abnormal temperature year 2004, 2005 and 2008, Qaidam Basin shows a warming trend over 16 years. The spatial distribution of the mean temperature is highly consistent with the elevation distribution of the region (Figure 5c). That is, there is a ring declining trend from the lowland of the basin center to the mountains around the basin, as well as from the small mountain basin or valley to the ridge and mountain peak. In terms of precipitation, the average precipitation of 16 a is 131.63 mm, showing a tendency to increase first and then decrease (Figure 5b). Qaidam Basin is located in the inland and surrounded by mountains, so it is difficult for water vapor to reach there. The mid-west presents an extremely arid climatic characteristic, while the eastern low mountainous area and the southern slope of Kunlun Mountains is closer to the monsoon region, so the precipitation is much more. In summary, the mean annual precipitation of Qaidam Basin performs a semi-circular decreasing trend from southeast to northwest (Figure 5d).

In general, the climate tends to be increasingly warm-humid in Qaidam Basin. Interannual variation of temperature and precipitation of 16 a in Qaidam Basin are obtained with trend analysis method. The result shows that the overall trend of annual variation of temperature in Qaidam Basin is not very obvious (Figure 5e). Only the south slope of the eastern Kunlun Mountains passes the 0.05 significance test. The vegetation area is mainly characterized by no significant warming, while the temperature declines in the basin center where desert is distributed widely. In terms of interannual variation of precipitation, the precipitation of the eastern Basin, represented by the eastern Qilian Mountains and eastern Kunlun Mountains, is significantly increasing. To the west of the Basin, precipitation presents a trend of gradient decline. The significance test of the interannual variation of precipitation is conducted, and the result shows that precipitation increases significantly in the eastern Kunlun Mountains (Figure 5f).

4.3.2 The relationship between SGS and temperature and precipitation

The SGS is affected by both temperature and precipitation. In order to obtain the correlation between one of the dependent variables and the independent variable, the mean temperature and available precipitation in spring (from March to May) during 2000 to 2015 are extracted. And then with partial correlation analysis, the partial correlation coefficients between SGS and temperature and precipitation are obtained to conduct T tests (Figure 6). (1) According to the results of T tests, the area where temperature and SGS are significantly correlated (P<0.01 and 0.01⩾P<0.05) accounts for 7.45% of vegetation coverage area (Figure 6a). Of the area, the part with a significant positive correlation (P<0.01 and 0.01⩾P<0.05) accounts for 3.14%, which is distributed in the northeast of the basin and the high altitude areas of the southern slope of Qilian Mountains and Kunlun Mountains. The temperature, based on the above analysis, of these areas, rises obviously. However, since the rare precipitation there has been excluded in the analysis, unilateral warming can lead to the increasing evaporation and the destruction of soil moisture to postpone SGS. The areas with the significant negative correlation (P<0.01 and 0.01≥P<0.05) accounts for 4.31%, which is distributed in the north, southwest of Qaidam Basin and alluvial and diluvium fan in the basin center, such as the northern slope of Qilian Mountains and some river valleys in the west of Kunlun Mountains. There is much runoff supply. Therefore temperature rising is beneficial to the increase of the runoff amount, which mainly comes from the melted-water, and thereby the soil moisture will be improved and SGS will advance.

(2) The area where there is a significant correlation (P<0.01 and 0.01≥P<0.05) between SGS and spring precipitation only accounts for only 7.41% (Figure 6b), which is probably related to the poor and unstable precipitation. In spite of this, with precipitation increasing, there are still 6.6% of the areas whose SGS advances in the vegetation area. The areas are distributed in the valley area of southern slope of Kunlun Mountains and Qilian Mountains. It is of proof once again that climate warming leads to SGS being delayed without runoff supply in the Qaidam Basin where precipitation is poor. When the precipitation becomes abundant in some years, soil moisture will become better to drive SGS ahead of time.

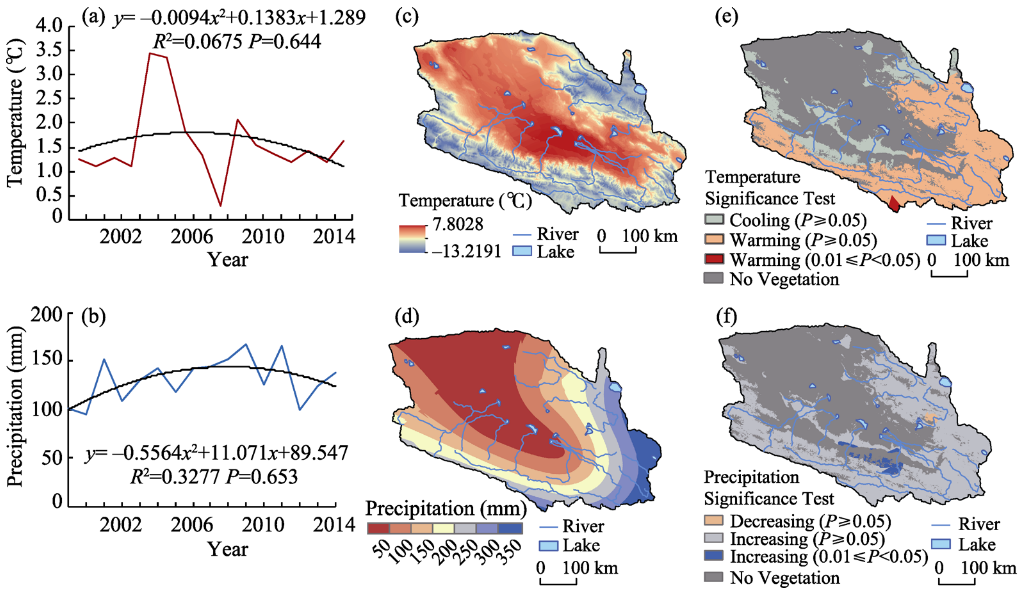

Figure 5 Spatial and temporal distribution of temperature and precipitation (a–d), and their significance (e, f) in Qaidam Basin during 2000–2015

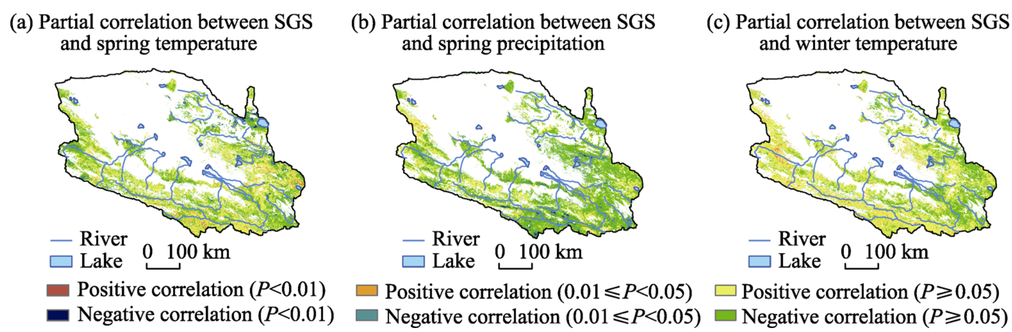

Figure 6 The relationship between SGS and spring temperature (a), as well as spring precipitation (b) and winter temperature (c) in Qaidam Basin

(3) Studies have shown that winter temperature on Qinghai-Tibet Plateau has a greater impact on SGS, even greater than spring temperature (Li *et al*., 2010; Ding *et al*., 2011). On the basis of the analysis, it is revealed that the areas where winter temperatures relate to SGS in Qaidam Basin account for 4.17% (Figure 6c). It can be revealed that the impact of the two on SGS is roughly close to each other. Nevertheless, the affected areas are slightly different, and the obvious areas such as the high altitude ridge of Kunlun Mountains where the temperature rising will cause the SGS to postpone in the following year. Water in these areas is dominated by precipitation, while the winter precipitation is scarce or even none. At this time, warm winter will exacerbate the evaporation to lead to the spring drought, so that SGS will be delayed. The negative correlation between winter temperature and SGS is mainly in the eastern part of the basin. Due to the abundant water resources in this area, soil moisture is better, and warm winter may help drive the initial period at 0°C and 5°C ahead of time, so that SGS may be advanced.

4.3.3 The relationship between EGS and temperature and precipitation

EGS is closely related to the temperature and precipitation in both summer and autumn. Within the time frame of this study, the EGS in Qaidam Basin concentrates on the range of 270 d and 310 d (around October). In order to make the analysis result more accurately reflect the relationship between climate and phenology, in this paper, the monthly mean temperature and precipitation of September and October (2000–2015) of Qaidam Basin are selected to conduct partial correlation analysis (Figure 7). The result shows, (1) the areas with significant positive correlation between EGS and autumn temperature account for 3.69% ($P<0.01$ and $0.01 \geqslant P<0.05$), which are distributed in the upstream valley of the southeast and northeast of the basin (Figure 7a). Research conducted by Dai *et al*. (2013) shows that most rivers' discharge in Qaidam area increases year by year due to the rising temperature, which causes snow and ice to melt, and thus directly increases the flow of underground and aboveground runoff. Plant growth conditions have been improved, thus delaying EGS. The areas where EGS and autumn temperature are significantly negatively correlated account for 1.29% ($P<0.01$ and $0.01 \geqslant P<0.05$), and are mainly distributed in the eastern part of Kunlun Mountains. The elevation is about 4500 m above sea level, and the alpine meadow distributed here is extremely sensitive to the climate. Significant warming and intense evaporation lead to water shortage, and thus vegetation advances into EGS. (2) By 0.01 and 0.05 significance tests, it is shown that the areas where EGS and autumn precipitation are significantly positively correlated accounts for 6.89%. They are distributed in the northern slope of Qilian Mountains such as the upstream of Bayinguole River and Dahaleteng River, Har Lake around and the eastern part of Kunlun Mountains (Figure 7b). In particular, the significantly increased precipitation in the eastern section of Kunlun Mountains provides favorable hydrothermal conditions for vegetation growth.

In general, in Qaidam Basin, there are extreme drought and significant differentiation in altitude, so that increased autumn temperature may cause severe evaporation. And then due to lack of water, the plants are withered in advance. In contrast, precipitation can quickly and effectively replenish the water required for the plant, and then delay EGS significantly.

4.3.4 The relationship between LGS and temperature and precipitation

LGS can reflect the status of vegetation growth in a region, and indirectly reflect the perennial hydrothermal condition there. Analysis shows that the area where there is a positive correlation between LGS and annual mean temperature is larger than with a negative correlation (Figure 8). 6.43% of the vegetation coverage area is significantly positively correlated with temperature (P<0.01 and 0.01≥P<0.05), and it is concentrated in the eastern mountains and the upstream of some valleys in Qilian Mountains and Kunlun Mountains (Figure 8a). The negative correlation with annual mean temperature is mainly represented by the southeastern margin of Kunlun Mountains, with a significant correlation accounting for 2.23% (P<0.01 and 0.01≥P<0.05). It can be revealed from the above analysis that the warming of the eastern Kunlun Mountains in the basin is significant, and the interannual variation trend of LGS there is significantly shortened. Heat plays a leading role in this trend. This is caused, though the SGS change here is not significant, by the temperature increases and the evapotranspiration increases, which lead to the advancing of EGS and then the shortening of LGS.

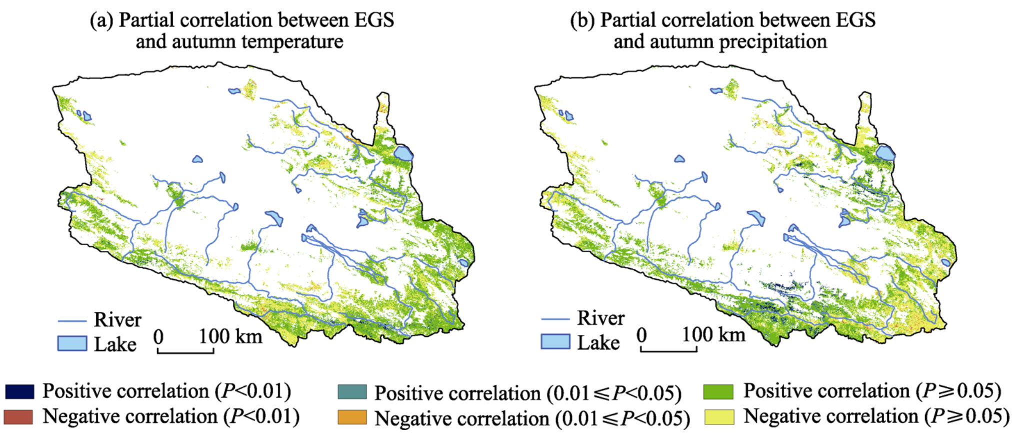

Figure 7 Partial correlations between EGS and autumn temperature (a), as well as autumn precipitation (b) in Qaidam Basin

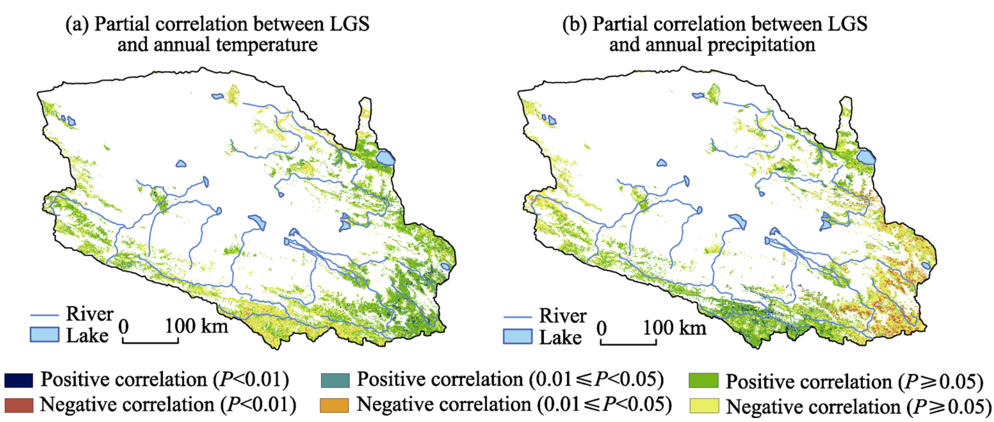

Figure 8 Partial correlations between LGS and annual temperature (a), as well as annual precipitation (b) in Qaidam Basin

In contrast to the temperature, there are more areas where there are negative correlations between precipitation and LGS, accounting for 13.5% of vegetation coverage. These areas are represented by the eastern low mountains, lacustrine plain, river upstream and so on (Figure 8b). Maybe due to the relatively abundant precipitation and water sources, the areas are not sensitive to the weak increase or decrease of precipitation. Other areas account for about 3.1% of the vegetation cover area, such as the eastern part of the Kunlun Mountains, where precipitation is significantly increased. If the interference of temperature rising is excluded, LGS there will extend with precipitation increasing.

5 Conclusions

(1) The spatial variation of plant phenology in Qaidam Basin shows a significant banded structure and vertical gradient characteristics, the differences from the mountains on the basin edge, to river-valley, alluvial and diluvial fan, and then to the oasis in the basin center. Meanwhile, phenology has a regular change from the eastern low mountains and central oasis areas to the mountains located in the north and south. From the east and center of the basin to the north and south sides SGS is gradually delayed, EGS gradually advanced, and LGS is gradually shortened, especially in the southeast of Qaidam Basin, LGS is shortened significantly. In addition, SGS is delayed and LGS is shortened in the oasis and river downstream where there is insufficient runoff supply.

(2) In Qaidam Basin, SGS and EGS overall delayed, and LGS shortened. Specific analysis showed that SGS postponed 0.36 d/16 a, EGS delayed 0.04 d/16 a, LGS shortened 0.32 d/16 a. This matches the conclusion from the study on phenology of southern Qinghai of Zhang *et al*. (1999) and Yu *et al*. (2004). It mainly reflects spatial difference. LGS generally shows a shortened trend except for the central oasis, east of the basin, the northern low mountainous areas of Qilian Mountains, etc.

(3) Plant phenology in Qaidam Basin presents significant spatial heterogeneity and altitude dependence. Due to different hydrothermal combinations at different elevations, SGS is delayed, EGS is advanced, and LGS is shortened along with the altitude rising. The occurrence of inflection points may be related to the changes of hydrothermal combination along with altitude rising. The phenology has a big variation in the area below 3000 m and above 5000 m. One reason for this is the foothills or oasis area has a wide variety of vegetation types or is the ecotone of agriculture and animal husbandry. And the other reason is that the vegetation species in the area above 5000 m are simple, whose growing power is very weak and the growth and development is sensitive to hydrothermal variations and climate changes. These two reasons lead to different LGS at the same elevation.

(4) A significant correlation between temperature distribution and elevation is found in Qaidam Basin. The trend presents gradual diminishing rings from the basin center to the edge. From 2000 to 2015, temperature's overall trend matches that of the global trend, and with a slight increase along with a big fluctuation. The temperature in vegetation coverage area is dominated by warming. The plateau of the eastern part of Kunlun Mountains represents a significant warming trend. There is an obvious interannual precipitation increment with gradual decrease from the eastern edge to the center and the west of Qaidam Basin.

(5) On the whole, the effect of precipitation on plant phenology of Qaidam Basin is greater than that of temperature, but there are differences in the degree of the effect in different regions. Firstly, areas represented by the valley, basin, lacustrine plain, and oasis, with their good soil moisture content, are highly sensitive to temperature, but not to precipitation. The increased temperature is favorable to the dormant plants in their passing through 0°C and 5°C in advance and can prompt them to sprout and turn green. Secondly, in the high-altitude mountain areas of the basin edge and the outer zone of some oasis areas, the plant phenology has a significant response to the changes of both temperature and precipitation. In some areas, precipitation is not enough, and the unilateral increase of temperature leads to evaporation increases, which may be the reason for SGS being delayed and EGS being advanced in these areas. And in other areas, the precipitation increases significantly, which can improve the hydrothermal condition. Meanwhile, SGS will be advanced and EGS will be delayed.

In this study, due to the lack of ground-based verification of the phenological time series, to some extent, the reliability of phenology data sources and monitoring indicators could be affected. The spatial and temporal changes of plant phenology are the result of comprehensive factors, while there are only the temperature and precipitation selected in this study without solar radiation quantity, evapotranspiration, humidity, hydrology, soil temperature and humidity, human activities and so on, which could be added in future studies for further analysis.

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