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Spatio-temporal variation of spring phenology in Tibetan Plateau and its linkage to climate change from 1982 to 2012

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Abstract: The influence of climate change on vegetation phenology is a heated issue in current climate change study. We used GIMMS-3g NDVI data to detect the spatio-temporal dynamics of the start of the growing season (SGS) over the Tibetan Plateau (TP) from 1982 to 2012 and to analyze its relationship with temperature and precipitation. No significant trend was observed in the SGS at the regional scale during the study period (R^2 = 0.03, P = 0.352). However, there were three time periods (1982-1999, 1999-2008 and 2008-2012) with identifiable, distinctly different trends. Regions with a significant advancing trend were mainly scattered throughout the humid and semi-humid areas, whereas the regions with a significant delaying trend were mostly distributed throughout the semi-arid areas. Statistical analysis showed that the response of the SGS to climate change varies spatially. The SGS was significantly correlated with the spring temperature and the start of the thermal growth season (STGS) in the relatively humid area. With increasing aridity, the importance of the spring temperature for the SGS gradually decreased. However, the influences of precipitation and winter temperature on the SGS were complicated across the plateau.

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Introduction

The influence of climate change has become increasingly obvious in a number of social and ecological systems since the 1970s (Rosenzweig et al. 2008). Plant phenology, the timing of recurring biological cycles and their connection to climate, is thought to be one of the most sensitive and valuable biosphere indicators of climate change (Badeck et al. 2004). In recent decades, shifts in the timing of plant growth have been observed worldwide (Parmesan and Yohe 2003;

Walther 2003; Cook et al. 2012). These shifts may influence the timing of vegetation activity as well as global carbon cycles (Penuelas et al. 2004; Churkina et al. 2005). Furthermore, the changes in plant phenology are of great significance in terms of biodiversity (Both et al. 2006), grain production (Memmott et al. 2007; Meroni et al. 2014) and climate change through biophysical feedback mechanisms (Penuelas et al. 2009; White et al. 2009). Ding et al. (2013) reported that changes in the duration of the growth season will significantly affect animal production in pasture areas.

Changes in vegetation phenology and their links to climate change are poorly understood in some regions with harsh natural conditions. This limits our ability to detect regional vegetation growth (Tang et al. 2009). Over the past couple of decades, the accessibility of information from global remotely sensed data has provided the possibility of studying the patterns and dynamics of global vegetation growth (Zhang et al. 2005; Rembold et al. 2013). Time series data composed of multi-resolution satellite images can objectively detect global-scale changes in vegetative phenology on a uniform timescale and have therefore been used to study phenology patterns relating to climate variability and human actions (Kathuroju et al. 2007; Seghieri et al. 2009; Zhang et al. 2009). Various techniques have been developed to derive vegetation phenology from satellite time series data set (White et al. 2009; Schwartz and Hanes 2010; Hmimina et al. 2013). The Tibetan Plateau (TP) is the highest plateau on earth, and it has a wide range of alpine grasslands, which have a high sensitivity to environmental changes (Piao et al. 2006a, Sun et al. 2012, Deng et al. 2013). Although long-term phenological observation data are lacking for the TP due to its severe physical environment, remotely sensed data, such as time-series Normalized Difference Vegetation Index (NDVI) data from Global Inventory Modeling and Mapping Studies (GIMMS), SPOT-VEGETATION (SPOT-VGT) and Moderate Resolution Imaging Spectroradiometer (MODIS) are available.

In recent decades, this plateau has experienced substantial warming (Liu and Chen 2000; Ding et al. 2014; Gao et al. 2014), which has resulted in an obvious change in phenology (Yu et al. 2010; Piao et al. 2011; Shen et al. 2011; Song et al. 2011; Ding et al. 2013; Fan et al. 2013). However, there are different views on why the advancing trend in SGS had stalled by the end of the 1990s (Yu et al. 2010, Piao et al. 2011; Shen et al. 2011; Ding et al. 2013; Fan et al. 2013; Shen et al. 2013; Zhang et al. 2013; Zhou et al. 2014). It is well known that climate change may alter vegetation phenology, but both the phenology and the climate controls are spatially heterogeneous (Piao et al. 2011; Shen et al. 2011). Regional differences in the changes in phenology not only reflect on current regional climate signals, but may be enhanced or dampened by different temperature sensitivities across climate regions and vegetation types (Cleland et al. 2006; Sherry et al. 2007). The TP has unique geographical conditions that create a distinct environmental gradient from the southeast to the northwest (Ding et al. 2007; Piao et al. 2004), and this spatial heterogeneity of the environment may lead to a diversity of phenological responses to climate change across the plateau (Ding et al. 2013; Piao et al. 2011; Shen et al. 2011). Thus far, however, there have been very few studies of the spatial pattern of the relationship between the SGS and climatic factors across the entire region, which has severely restricted our understanding of the variations in phenology across the TP within the context of climate change.

The purpose of this study was to detect the spatial and temporal changes in the start of the growing season (SGS) and its linkage to climate factors on the TP from 1982 to 2012 using GIMMS-3g NDVI. More specifically, we aimed to answer the following questions: (1) What was the spatial pattern of changes in SGS from 1982 to 2012 in the TP? (2) How did the SGS respond to climate change? (3) Is there a heterogeneous response of SGS to climate change?

1 Materials and Methods

1.1 Study area

The TP is located in western China (Figure 1). It has an average altitude of approximately 4000 m above sea level and an area of approximately 2.57×10^6 km^2 (Zhang et al. 2002). The temperature is generally higher in the southeast, where altitudes are low, but it is very cold in the northwest, where altitudes are higher. Precipitation mainly occurs in

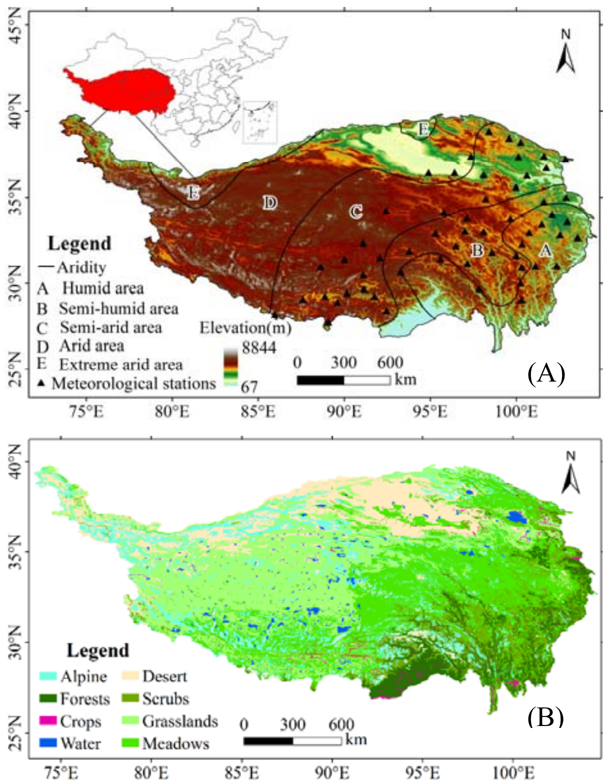

Figure 1 Spatial patterns of (A) aridity and elevation and (B) vegetation types on the Tibetan Plateau. The 57 meteorological stations used in this study are also shown.

the May to September period, and the mean annual precipitation decreases from more than 1000 mm to 50 mm from the southeast to the northwest. These patterns of precipitation and temperature result in the aridity increasing from the southeast to the northwest (Figure 1A).

The TP has approximately 1,521,500 km^2 of alpine grasslands accounting for 59.15% of the total area (Ding et al. 2013), which includes alpine meadows, alpine steppes, and alpine deserts. Recent studies have indicated that the grassland ecosystems of the TP play a significant role in the ecological security of China and East Asia (Sun et al. 2012). However, there is an extensive area with sparse or absent vegetation in the cold and dry west. To minimize the impact of bare, sparsely vegetated and evergreen regions, we only used pixels that simultaneously met the following criteria: (1) the average NDVI value in April–September shall be more than 0.10; (2) the maximum annual NDVI value shall exceed 0.15; (3) the annual maximum NDVI value occurring between July and September; and (4) the average winter NDVI value shall be less than 0.4 (Shen et al. 2011; Ding et al. 2013).

1.2 Data set

NDVI, defined as the ratio of the difference between near-infrared reflectance and red visible reflectance to their sum, is available to compare the seasonal and inter-annual changes in vegetation growth and activity (Myneni et al. 1997; Huete et al. 2002). In this study, we detected the SGS using GIMMS-3g NDVI (1982-2012) and SPOT-VGT NDVI (1999-2012) data set.

1.2.1 NDVI data set from GIMMS-3g

The GIMMS-3g NDVI data set, the longest time-series NDVI dataset, covering the period from 1981 (July) to 2012, were obtained from the Advanced Very High Resolution Radiometer instrument onboard the National Oceanic and Atmospheric Administration (NOAA) satellite series. The GIMMS-3g NDVI products, with a spatial resolution of 8 km, were compiled by merging segments (data strips) of half-month periods using the Maximum Value Composition (MVC) method (Holben 1986). These data had been calibrated for sensor shifts and corrected to remove the effects of sensor degradation, satellite orbital drift, solar zenith angles and volcanic aerosols.

1.2.2 NDVI data set from SPOT-VGT

The SPOT-VGT NDVI data set, covering the period from 1998 (April) to 2012 with a spatial resolution of 1 km, was derived from the vegetation instrument of the Système Pour l'Observation de la Terre (SPOT). It was compiled by merging 10-day segments (data strips) using the MVC method to minimize non-vegetation effects. The data had been preprocessed by the Vegetation Processing Centre at the Flemish Institute for Technological Research in Belgium (Maisongrande et al. 2004). A series of processes, including atmospheric correction, radiometric correction and geometric correction, were performed to ensure the quality of the data. The purpose of using this data set here is to validate the results derived from the GIMMS-3g.

1.2.3 Meteorological data

To investigate the relationship between the SGS and climate, we obtained daily meteorological data from 57 meteorological stations distributed across the TP (Figure 1A) and operated by the State Meteorological Administration of China (http://cdc.nmic.cn). These data, which spanned the 1982 to 2012 period, included the daily mean temperature (T_{mean}), daytime temperature (T_{max}), nighttime temperature (T_{min}) and precipitation.

1.2.4 Preprocessing of NDVI data

Despite all of the efforts to improve the data quality, there were spurious changes in vegetation indices resulting from inevitable atmospheric contamination in the data set (Chen et al. 2004) which may affect the detection of the vegetation SGS. For the purpose of reducing contamination by clouds, snow and ice, the Savitzky-Golay (S-G) filtering technique was applied to each annual NDVI curve (Chen et al. 2004). As a result of this filtering procedure, two types of data were obtained: one consisted of smoothed data with the same temporal resolution as the raw data, while the other was smoothed data with a temporal resolution of 1 day.

1.3 Climatological variables

There is currently no universal method to define the start of the thermal growing season (STGS) (Linderholm 2006). Robeson (2002) described the STGS as the date of the last spring freeze (i.e., a daily minimum temperature of<0°C). Other workers have defined the STGS based on temperature thresholds in a predefined number of days (Linderholm et al. 2008, Walther and Linderholm 2006). In this study, we used the definition of the STGS reported by Linderholm et al. (2008) and Dong et al. (2012). Namely, STGS is defined as the last day of the first 6-day period with a daily mean temperature greater than 5°C after the last spring frost (daily mean temperature <0°C).

To investigate the response of the SGS to the change in climate, we performed partial-correlation analyses between SGS and climate variables over the last 31 years. Sensitivity analyses were conducted to evaluate the effects of temperature and precipitation in different lengths of the pre-season period (15, 30 and 60 days) on spring phenology. All of the pre-season periods were specified to end on the same date, which was calculated by averaging the SGS over the all years. We then computed the mean temperature and cumulative precipitation of each pre-season period preceding this date for each year.

1.4 Detection of vegetation SGS from satellite images

Many methods have been developed to retrieve phenology from seasonal NDVI data (White et al. 2009; Cong et al. 2012). The most widely used methods include: the threshold of maximum relative change, used by Piao et al. (2006b, 2011) and Ding et al. (2013); the threshold of maximum relative change ratio, used by Zhang et al. (2013); the threshold of NDVI ratio, used by White et al. (1997) and Yu et al. (2010); and the maximum change in curvature, used by Zhang et al. (2003). However, a universally accepted method does not exist. In this study, we applied a threshold for the NDVI ratio, developed by White et al. (1997) to derive the SGS. We first found the maximum and minimum NDVI values based on the smoothed data with the same temporal resolution as the raw data (Figure 2A). Yu et al. (2010) evaluated the

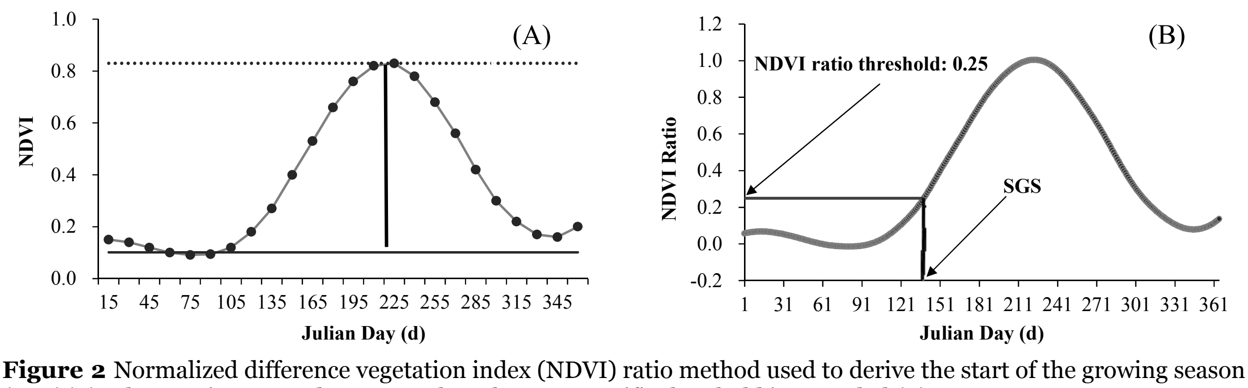

Figure 2 Normalized difference vegetation index (NDVI) ratio method used to derive the start of the growing season (SGS)(A). The SGS is assumed to occur when the SGS-specific threshold is exceeded (B).

average NDVI curve over 24 years (GIMMS) and noted that the NDVI reached its minimum value in February and March. To eliminate the influence of snow cover, the annual NDVI minimum was replaced by the average NDVI in these two months. Then, based on the smoothed data with a resolution of 1 day, we calculated the NDVI ratio using the following formula.

$$NDVI_{ratio} = (NDVI_{(t)} - NDVI_{min})/(NDVI_{max} - NDVI_{min}) \quad (1)$$

Where t is the time. The appropriate threshold was determined using ground observation data from 18 grassland-monitoring stations. The final thresholds were selected by considering two indicators, the mean absolute error (MAE) and the root-mean-square error (RMSE), which were calculated between the ground observations and the modeled SGS. Finally, we selected an NDVI ratio threshold of 0.25 (MAE = 10.66 d and RMSE = 13.41 d) for the SGS (Figure 2B).

2 Results and Discussion

2.1 Change in SGS at the regional scale

Figure 3 illustrates the inter-annual variation of the vegetation SGS from 1982 to 2012. No statistically significant trend could be found for the vegetation SGS over the entire study period (R^2 = 0.03, P = 0.352), although three distinctly different trends in the 1982-1999, 1999-2008 and 2008-2012 periods were identified. The SGS advanced by 0.20 days year^{-1} from 1982 to 1999 (R^2 = 0.15, P = 0.109). There was then a short delaying trend after 1998, which resulted in the SGS advancing more significantly (R^2 = 0.72, P = 0.02) from 1999 to 2008 than in the 1982-1999 period. The SGS advanced significantly by 0.14 days year^{-1} from 1982 to 2008 (R^2 = 0.18, P = 0.027), but the trend toward an earlier SGS then reversed after 2008, when there was an abrupt delaying trend.

The accuracy of the SGS results obtained in this study could be assessed through a comparison with the findings of previous studies. At the regional scale, the trend in the annual changes in the SGS for the 1982-1998 periods is in agreement with the results of Yu et al. (2010) and Piao et al. (2011), who used GIMMS (1982-2006). Similarly, the trend for the 1999-2008 periods is in accordance with the findings of Ding et al. (2013) and Shen et al. (2011), who used SPOT-VGT NDVI. However, the trend is different from the results of Song et al. (2011) and Zhang et al. (2013) who used MODIS and GIMMS-3g, respectively, especially for the period after 2008. Zhang et al. (2013) suggested that the GIMMS NDVI data may have severe data-quality issues in most parts of the western plateau. By merging GIMMS-based SGS data from 1982 to 2000 with the SGS based on SPOT-VGT data from 2001 to 2011, they found that the alpine vegetation SGS experienced a continuous advancing trend from 1982 to 2011. Ding et al. (2015) also suggested that it is important to pay attention to the types of vegetation with high or low coverage when studying vegetation phenology in the TP using remote sensing techniques.

In the present study, we compared the consistency of the SGS values derived from GIMMS-3g and SPOT-VGT data (Figure 4) and found a correlation coefficient of 0.46 (P = 0.099) between the GIMMS-3g and SPOT-VGT data for 1999–2012. The SGS values derived from SPOT

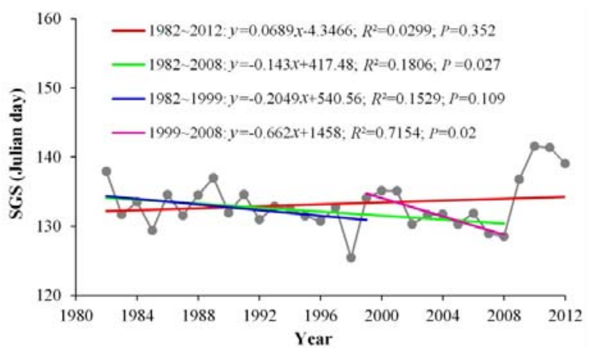

Figure 3 Inter-annual variation in start of the growing season (SGS) of the vegetation for the entire study area from 1982 to 2012, derived from GIMMS-3g NDVI data.

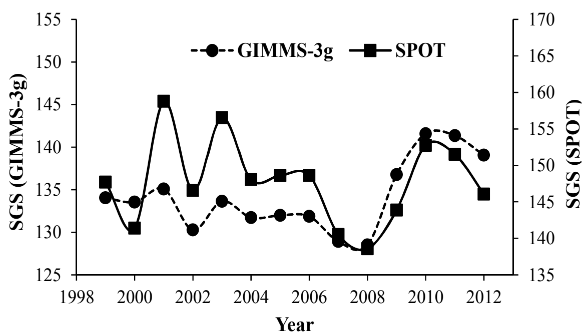

Figure 4 Comparison of inter-annual variation in start of the growing season (SGS) derived from SPOT and GIMMS-3g data sets from 1999 to 2012.

and GIMMS show the same sudden delaying trend after 2008. Furthermore, the results of a few previous studies found the same phenomenon. Fu et al. (2014) compared the inter-annual variability of the SGS values from MODIS products and four phenology models and found the SGS values for grassland also showed a delaying trend from 2008 to 2010 over the northern hemisphere. To account for the potential uncertainty in different phenology models based on remote sensing, Cong et al. (2013) conducted a multi-method investigation to quantify changes in the SGS from 1982 to 2010 over the temperature zones of China and also found that the SGS derived from most of the methods showed a delaying trend after 2008. The studies listed here all agree with the results of this study.

2.2 Spatial patterns of trends in the SGS

Figure 5 shows the spatial patterns in the trends of the SGS. There was a strong spatial heterogeneity throughout the plateau for the trend in SGS. During the entire study period (Figure 5A and Table 1), the number of pixels for which the delaying trend was significant ($P < 0.1$) corresponds to approximately 23.39% of the total number of pixels; these pixels were mainly distributed throughout the semi-arid areas. The regions with a significant advancing trend account for approximately 9.51% of the total, and they were scattered mainly throughout the humid and semi-humid areas. During the 1982-1999 period (Figure 5B and Table 1), the pixels with a significant advancing trend account for 17.72% of the total, and they were mainly distributed throughout the humid and semi-humid areas; these pixels were six times more numerous than those showing a significant delaying trend. There was a clear advancing trend throughout the entire plateau for the 1999-2008 period. As shown in Figure 5C and Table 2, the proportion of significant advancing pixels was 22.30%; these were mainly distributed in semi-humid and semi-arid areas and were 22 times more abundant than the pixels with a significant delaying trend. In general, for the 1982-2008 periods, the SGS values mostly show an advancing trend (Figure 5D). Based on the trend significance test ($P < 0.1$), approximately 27.66% of the pixels showed an advancing trend, which is much higher than the proportion of pixels with a

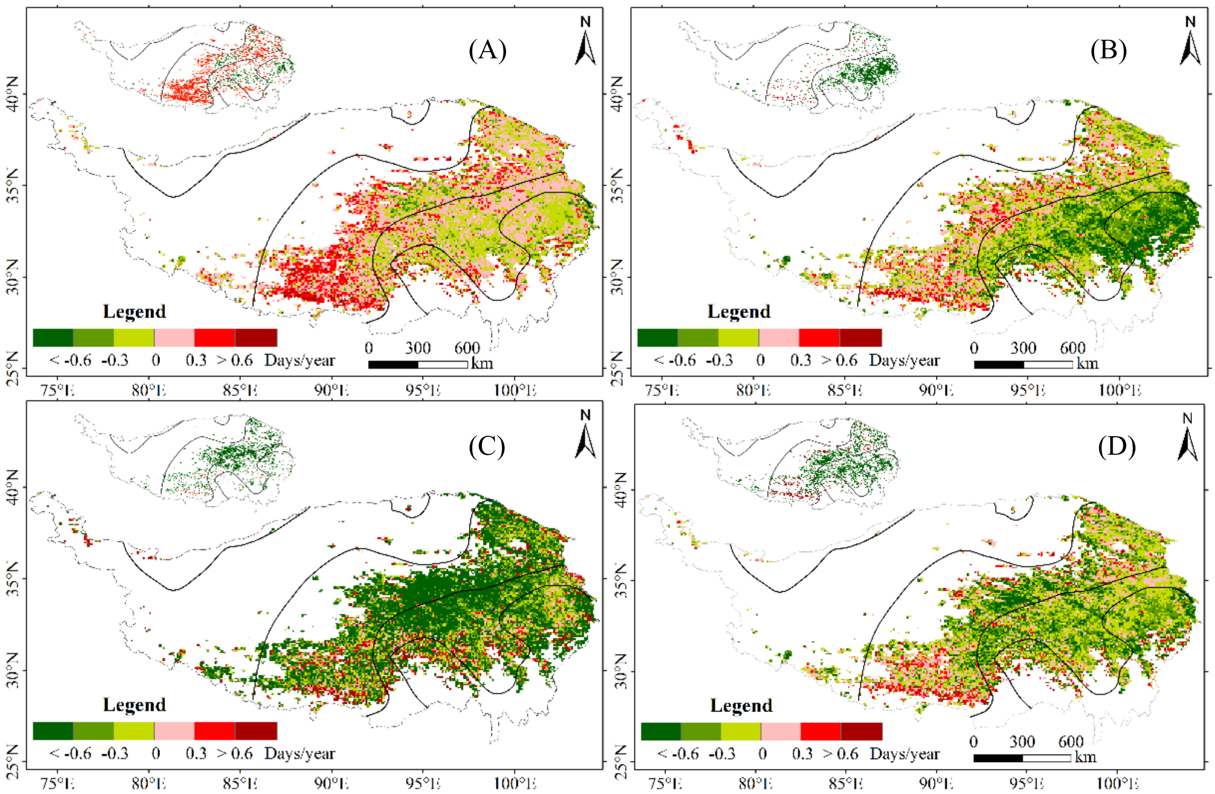

Figure 5 Spatial pattern of trends in the start of the growing season (SGS) values in the Tibetan Plateau. (A) 1982-2012; (B) 1982-1999; (C) 1999-2008; and (D) 1982-2008.The small map on top illustrates significant pixels ($P < 0.1$).

delaying trend (Table 2). The delaying trend of the entire study period is related to the larger delaying trend after 2008.

Table 1 Percentage of pixels with advancing or delaying trends of the start of the growing season (SGS)

	1982-1999	1999-2008	1982-2008	1982-2012
Pixels with advancing trend (%)	67.68	80.78	71.77	39.09
Pixels with significant advancing trend (%)	17.72	22.3	27.66	9.52
Pixels with delaying trend (%)	32.32	19.22	28.23	60.91
Pixels with significant delaying trend (%)	2.76	1.11	5.33	23.4

Table 2 Correlation between the start of the growing season (SGS) and winter and spring temperatures and precipitation for the meteorological stations

Study area	Period	*R* (SGS)		
		Apr-May (MT_{mean})	Apr-May（SP）	Winter (MT_{mean})
Humid	1982-1999	-0.65***	-0.08	-0.17
	1982-2008	-0.62***	-0.02	-0.14
	1999-2008	-0.55	0.27	-0.05
	1982-2012	-0.36**	0.09	-0.05
Semi-humid	1982-1999	-0.48**	0.04	0.17
	1982-2008	-0.57***	0.06	0.02
	1999-2008	-0.50	0.57*	0.13
	1982-2012	-0.23	0.19	0.18
Semi-arid	1982-1999	-0.18	0.25	-0.03
	1982-2008	-0.37*	0.03	-0.25
	1999-2008	-0.26	0.00	-0.11
	1982-2012	0.09	0.18	0.14

Notes: MT_{mean}: mean of daily mean temperature; *SP*: sum of precipitation; ***: $P < 0.01$;**: $P < 0.05$;*: $P < 0.1$.

2.3 Correlation between SGS and climate factors

2.3.1 Temperature thresholds for SGS

The relationship between temperature or cumulative temperature at the date of the SGS and the mean temperature across all 57 meteorological stations (Figure 6) indicates that the temperature threshold of the SGS is significantly and positively correlated with the mean annual temperature ($R^2 = 0.65$, $P < 0.001$) and that the cumulative temperature threshold is also significantly and positively correlated with the mean annual temperature ($R^2 = 0.81$, $P < 0.001$). These results indicate that, in contrast to the vegetation in warmer areas, vegetation in colder environments demanded a lower threshold temperature for green-up (Jin et al. 2013). Extrapolating space for time, we can infer that, in the context of future global warming, the vegetation SGS may require a higher threshold temperature (Piao et al. 2011). Such an increase in the SGS threshold in response to a rising mean annual temperature may be attributed to the acclimation of vegetation to higher temperatures

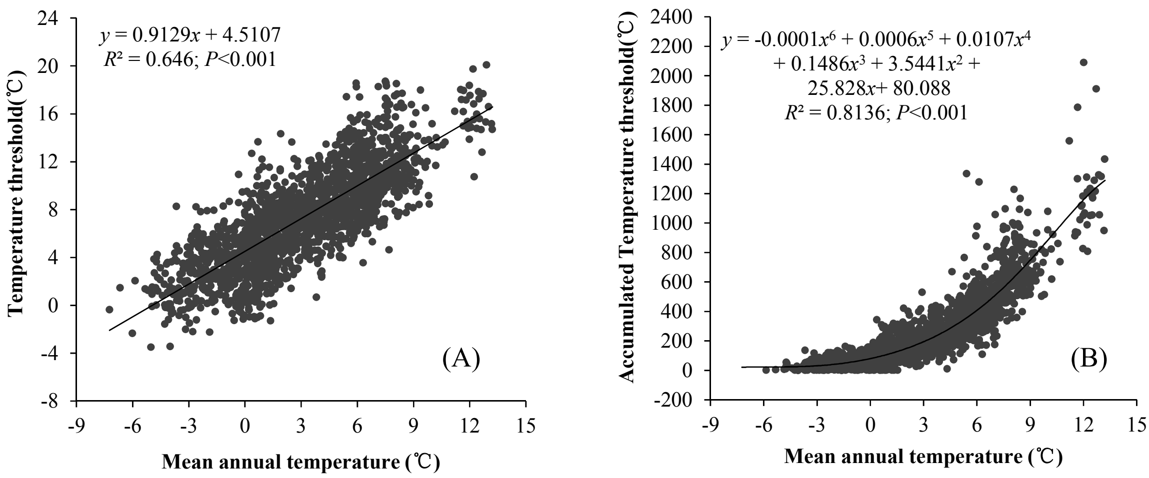

Figure 6 Relationship between temperature threshold of start of the growing season (SGS) and mean annual temperature across meteorological stations in the Tibetan Plateau. (A) Temperature threshold and (B) accumulated temperature threshold.

(White et al. 1999, Piao et al. 2011). The observed dependence of the SGS on the mean annual temperature suggests that a 1°C increase in the mean annual temperature of the TP would increase the temperature threshold of the vegetation SGS by 0.86°C; this is in agreement with the results of Piao et al. (2011) and Jin et al. (2013). The conclusions above, however, are merely inferred from remote sensing data alone; additional research is required to determine whether these results indicate that an increased temperature was required for the SGS at a given location or cumulative temperature with the global climate warming (Shen et al. 2011).

2.3.2 Correlation between SGS and STGS

Figure 7 shows the relationship between the SGS and the STGS. Across the entire study area, the STGS is significantly and positively correlated with the SGS from 1982 to 2008 (R^2 = 0.258, P = 0.007), although there was a spatial heterogeneity throughout the plateau between the different regions. For the humid area, the STGS is significantly and positively correlated with the SGS from 1982 to 2008 (R^2 = 0.40, P < 0.001). However, in the semi-humid and semi-arid areas, although the STGS was also significantly and positively correlated with the SGS from 1982 to 2008, the significance levels are lower than those of the humid areas. These results indicate that the change in spring temperature has an important effect on on the SGS in the TP, although the significance is different in different areas. In the semi-humid and semi-arid areas, the importance of temperature is lower than that in the humid areas. As a result of the abrupt delay after 2008, the STGS had no significant correlation with the vegetation SGS over the whole study period.

2.3.3 Correlation between SGS and temperature and precipitation

Previous research using GIMMS NDVI data sets has shown a prominent reversal of the SGS on the TP at the end of the 1990s, with a significant trend of an advancing SGS from 1982 to 1998 and a trend of a delayed SGS from 1998 to 2006 (Yu et al. 2010; Piao et al. 2011; Ding et al. 2013). The reported causes for the delay in SGS on the TP are diverse and include opposite spring temperature trends in the two periods (Piao et al. 2011) and winter warming resulting in a failure to sufficiently chill the plants in the winter (Yu et al. 2010). In the present study, we extended the time series to 2012 and found that the response of SGS to spring temperature is more sensitive than the response to

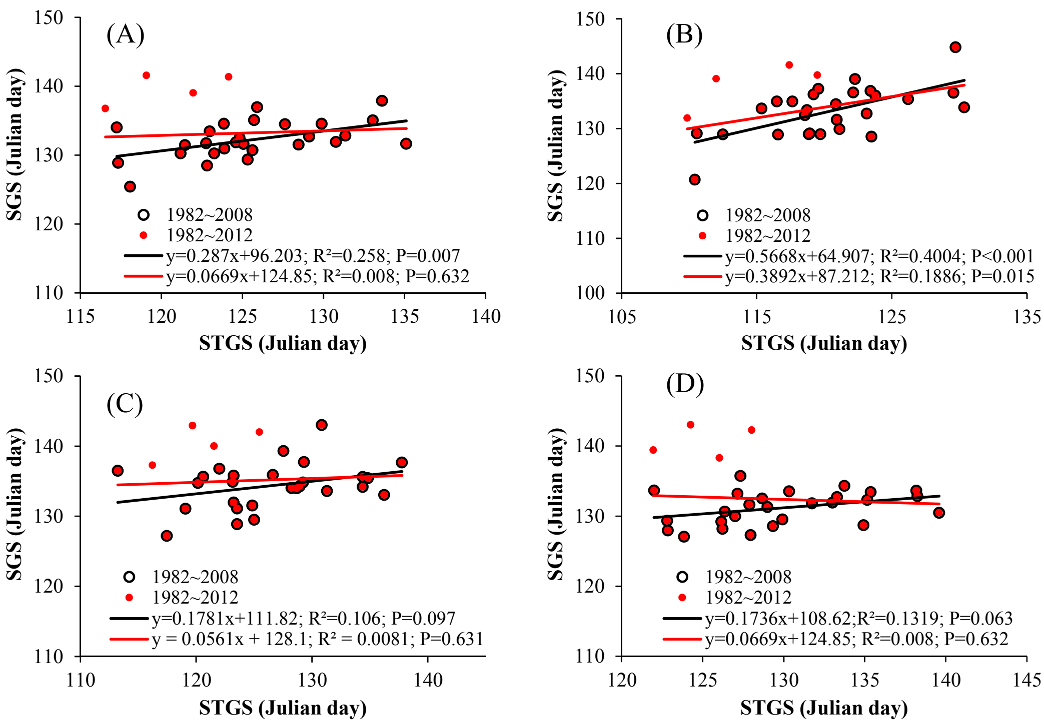

Figure 7 Relationship between the start of the growing season (SGS) and thermal growth season (STGS) across meteorological stations (A) over the whole study area, (B) in the humid areas, (C) in the semi-humid areas, and (D) in the semi-arid area.

the cumulative spring precipitation and winter temperature. However, there was a spatial heterogeneity for this response. With increasing aridity, the intensity of the influence of temperature on the SGS gradually decreases (Table 2).

Based on the GIMMS-NDVI data sets from 1982 to 2006, Shen et al. (2011) concluded that in relatively moist areas, the SGS tended to be advanced by the increasing pre-season temperature. Cong et al. (2013) found that with the increase in cumulative pre-season precipitation, the responses of spring phenology to temperature became intense across the northern part of China. They also found that when the length of the pre-season period was >120 days, there was a significant reduction in the number of stations with a negative correlation between spring phenology and temperature. In this study, we also found that the temperature was a key climatic factor influencing the SGS in the relatively moist areas. However, with increasing aridity, the importance of temperature was gradually reduced. As the length of the pre-season period was extended, the importance of temperature first increased and then decreased. The relationship between the SGS and the MT_{mean} for the 30 d period before SGS is the strongest (Table 3).

Piao et al. (2015) found the vegetation green-up in spring is triggered more by the daytime temperature (T_{max}) than by the nighttime temperature (T_{min}). In our study, we also found the correlation between the SGS and T_{max} is better than that between SGS and $T_{min.}$ However, there was a spatial heterogeneity for the correlation. With increasing aridity, the intensity of the influence of temperature on the SGS gradually decreases. As the length of the pre-season period was extended, the importance of temperature first increased and then decreased. The relationship between the SGS and the MT_{max} for the 30 d period before SGS is the

Table 3 Correlation between the start of the growing season (SGS) and mean temperature and cumulative precipitation before the SGS

Study area	Period	MT_{mean} for x days before SGS			*SP* for x days before SGS		
		15 d	30 d	60 d	15 d	30 d	60 d
Humid	1982-1999	-0.75***	-0.76***	-0.58**	-0.17	0.38	0.31
	1982-2008	-0.71***	-0.68***	-0.49**	-0.12	0.29	0.22
	1999-2008	-0.43	-0.34	-0.27	-0.03	0.24	0.25
	1982-2012	-0.44**	-0.50***	-0.43**	-0.15	0.26	0.38*
Semi-humid	1982-1999	-0.51**	-0.60***	-0.35	-0.24	0.09	0.11
	1982-2008	-0.52***	-0.62***	-0.45**	-0.32	-0.04	-0.04
	1999-2008	-0.64*	-0.29	-0.42	-0.03	0.05	-0.22
	1982-2012	-0.10	-0.25	-0.17	-0.23	0.03	0.14
Semi-arid	1982-1999	-0.10	-0.13	0.05	-0.07	-0.06	-0.05
	1982-2008	-0.24	-0.30	-0.28	-0.25	-0.20	-0.22
	1999-2008	-0.49	-0.39	-0.51	-0.59*	-0.52	-0.64*
	1982-2012	0.15	0.15	0.16	0.15	0.18	-0.03

Notes: MT_{mean}: mean of daily mean temperature; *SP*: sum of precipitation; ***: $P < 0.01$;**: $P < 0.05$;*: $P < 0.1$.

Table 4 Correlation between the start of the growing season (SGS) and mean daytime temperature (T_{max}) and nighttime temperature (T_{min}) prior to the SGS

Study area	Periods	MT_{max} for x days before SGS			MT_{min} for x days before SGS		
		15 d	30 d	60 d	15 d	30 d	60 d
Humid	1982-1999	-0.76***	-0.78***	-0.53**	-0.66***	-0.66***	-0.58**
	1982-2008	-0.76***	-0.72***	-0.47**	-0.59***	-0.58***	-0.51***
	1999-2008	-0.75**	-0.41	-0.32	-0.05	-0.23	-0.24
	1982-2012	-0.49***	-0.55***	-0.39**	-0.31*	-0.39**	-0.47**
Semi-humid	1982-1999	-0.40	-0.52**	-0.38	-0.03	-0.22	-0.12
	1982-2008	-0.39**	-0.50***	-0.38*	-0.09	-0.30	-0.23
	1999-2008	-0.58	-0.06	-0.18	-0.77**	-0.44	-0.53
	1982-2012	-0.12	-0.26	-0.17	-0.08	-0.07	-0.08
Semi-arid	1982-1999	-0.20	-0.11	-0.15	0.03	-0.03	0.01
	1982-2008	-0.15	-0.27	-0.42**	-0.09	-0.24	-0.35*
	1999-2008	-0.36	-0.31	-0.46	-0.34	-0.63*	-0.72**
	1982-2012	-0.21	0.14	0.08	0.23	0.27	0.20

Notes: MT_{min}: mean of nighttime temperature (T_{min}); MT_{max}: mean of daytime temperature (T_{max}); ***: $P < 0.01$; **: $P < 0.05$; *: $P < 0.1$.

strongest (Table 4).

In our study, we found that the response of SGS to spring temperature is more sensitive than the response to winter temperature and precipitation. However, there was a spatial heterogeneity for the response. With the increase in aridity, the intensity of the influence of temperature on the SGS gradually decreases. The results are particularly obvious in the 1982-2008 period. Thus, we can explain that the variation in the SGS is driven by spring temperature change. To a certain degree, we also thought that the sudden delay of SGS after 2008 was caused by the spring temperature, which showed a decreasing trend after 2008 (Figure 8). Tao et al. (2013) also found an opposite trend in the annual average temperature in Qinghai and Xizang Province, which was obvious in daytime. However, the consistency between the SGS and spring temperature was not perfect because spring temperature influenced the SGS in relatively humid areas. This indicated that there were many factors beyond spring temperature which drive the SGS.

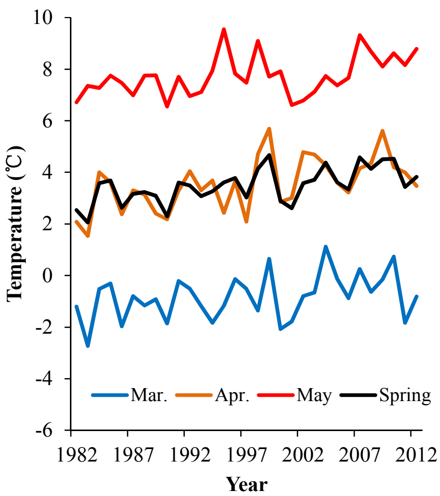

Figure 8 Inter-annual variation in spring temperature for the entire study area from 1982 to 2012.

3 Conclusions

Using the GIMMS-3g NDVI data set and concurrent meteorological records from 1982 to 2012, we explored the spatio-temporal changes in the SGS and characterized their relationship to temperature and precipitation on the TP. At the regional scale, no significant trend in the SGS was observed over the entire study period ($R^2 = 0.03$, $P = 0.352$). Three distinctly different trends in the 1982-1999, 1999-2008 and 2008-2012 periods were identified. From 1982 to 1999, the SGS advanced significantly, by 0.20 days year^{-1} ($R^2 = 0.15$, $P = 0.109$). However, there was a short delaying trend after 1998, which resulted in the SGS advancing more significantly from 1999 to 2008 ($R^2 = 0.72$, $P = 0.02$) than in the 1982-1999period. However, the trend toward an earlier SGS appeared to be reversed after 2008, when there was an abrupt delaying trend. With respect to the spatial pattern, the pixels for the delaying trend were mainly distributed throughout the semi-arid areas. The regions with a significant advancing trend were scattered mainly within the humid and semi-humid areas. For the 1982-2008 period, based on the trend significance test ($P < 0.1$), approximately 27.66% of the pixels showed an advancing trend, which was much higher than the proportion of pixels with a delaying trend. For the whole study area, a delaying trend was seen after 2008.

The temperature and cumulative temperature thresholds of the SGS were significantly and positively correlated with the mean annual temperature, which means that the vegetation SGS may require an increasing temperature threshold with global warming. Such an increase in the SGS threshold in response to an increasing mean annual temperature may be attributed to growth acclimation of vegetation to higher temperatures. Statistical analysis shows that the SGS is significantly correlated with the spring temperature and STGS in the relatively humid area. That is, the SGS is advanced with increasing spring temperatures and the advancement of the STGS. However, there is no relationship between the SGS and the winter temperature. The response of the SGS to climate change varies spatially, and we found that the importance of the spring temperature for the SGS gradually decreased with increasing aridity.

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