



Differences and variations in the elevation-dependent climatic growing season of the northern and southern slopes of the Qinling Mountains of China from 1985 to 2015

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Abstract

Based on daily mean temperature data from 32 meteorological stations in the study area, this paper discusses the relationship between the changes in the climatic growing season and altitude and the differences in the northern (NSQM) and southern (SSQM) slopes of the Qinling Mountains (QMs) from 1985 to 2015. Our analyses generated three primary results. First, the spatial distribution patterns of the growing season start (GSS), growing season end (GSE), and growing season length (GSL) exhibited an altitudinal gradient and differences between the NSQM and SSQM. The occurrence time of the GSS, GSE, and the GSL of the NSQM was approximately 15 days later, 10 days earlier, and 25 days shorter respectively than that of the SSQM. Second, the three factors exhibited regular changes with an increasing elevation gradient: the GSS, GSE, and GSL were gradually delayed, advanced, and shortened, respectively. In the area below 1800 m above sea level, the GSS, GSE, and GSL of the NSQM was later, earlier, and shorter, respectively, than that of the SSQM; while the changing trends in the three were opposite in the areas above 2700 m; and the three in the areas between 1800 and 2700 m varied little in the NSQM and SSQM. The sensitivities of the GSS, GSE, and GSL of the NSQM and SSQM to elevation also reflected in the trends of inter-annual variability. Third, among the different altitudinal vegetation belts from low-altitude to high-altitude areas, the occurrence time of the GSS and GSE and the duration of the GSL in the alpine meadow areas were all exchanged in the NSQM and SSQM. The GSS, GSE, and GSL of the NSQM were earlier, later, and longer respectively than that of the SSQM.

1 Introduction

Global climate warming is undoubtedly occurring, and there are obvious regional differences in the process. In general, warming is more obvious at higher latitudes than lower latitudes (Liu et al. 2008), and studies of the phenomenon of climate change in high-altitude areas of the middle and low latitudes demonstrate that surface warming is dependent on altitude (Diaz and Bradley 1997). Additionally, studies have

indicated that the response to global warming is more sensitive and intense in high-altitude regions than in lower altitudes (Yao et al. 2000). Surface warming tends to increase with altitude, and the warming in highland areas is more rapid (Beniston and Rebetez 1996; Giorgi et al. 1997; Fyfe and Flato 1999) and more obvious (Rangwala and Miller 2012; Qin et al. 2009) than in lowland areas.

The decrease in temperature with elevation also results in elevation dependence of plant phenological changes. The line “when the flowers and sages in the plains are decaying in April, but nowhere else in the mountains is the peach blossoming” from a verse expresses the differences in phenological phenomena caused by differences in the temperature at different altitudes. Some scholars have studied the relationship between altitude and vegetation phenology (Giménez-benavides et al. 2007; Qiu et al. 2013) and confirmed that elevation plays an important role in regional differences in phenology (Piao and Fang 2003). According to Hopkins’ law (Hopkins 1918), other conditions being equal, plant phenological events in temperate portions of North America is delayed by 4 days in spring and early summer and advanced

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by 4 days in the late summer and autumn but with additional factors when the temperate regions for each degree of latitude northward, for each 5° of longitude eastward, or for each 121.92 m increase in elevation. Pellerin et al. (2012) noted that elevation is an important factor that affects changes in vegetation phenology on the western slopes of the Alps, and with each 100 m increase in elevation, vegetation growth and leaf-expansion will be delayed by 2.4–3.4 days. In addition, the start and end times of vegetation phenology in subtropical mountainous areas of Fujian Province of China will be delayed with increasing elevation. Climate warming has a strong effect on plant growth, while changes in growing season (GS) can sensitively reflect the responses of terrestrial ecosystems to climate change, and GS has become an important index for indicating climate change (Linderholm et al. 2008; Song et al. 2009). Walther et al. (2002) found that warming over the past 30 years has had a significant effect on plant phenology, latitudinal and vertical changes in plant distribution, and the interactive processes among plants, and other scholars found that the responses of terrestrial ecosystems to global change exhibit strong spatial heterogeneity (Piao and Fang 2003). In the context of global change, the sensitivity of mountains to climate warming is second only to that of the polar regions, and the response of alpine regions to climate change is almost the same as in the Arctic. These responses indicate that the warming amplitude of mountainous areas is greater than that of plains at the same latitude, and the amplitude increases with elevation (Huber et al. 2005; UNGA 2004). Mountain ecosystems are sensitive indicators of the biological responses to global changes since their structures, processes, and functions as well as vegetation distribution patterns and succession are greatly affected (UNEP/WCMC 2002; UNGA 2004). In the context of global change, it is consequently of great importance to study the change in the GS in mountains, which are ecologically sensitive areas, with variation in altitude (Chen et al. 2015).

The Qinling Mountains (QMs) are known as “China’s backbone,” and they are not only the geographical boundary between northern and southern China, the demarcation line of China’s climate, and the ecotone of ecological environment and the ecologically vulnerable area in central China but an area sensitive to regional responses to climate change (Liu and Shao 2000). For nearly half a century, especially since the 1980s, the temperature in the QMs has been increasing (Bai 2014). By monitoring the GS of vegetation by back-casting MODIS EVI (Enhanced Vegetation Index) using remote-sensing data from 2001 to 2010, Xia et al. (2015) found that the distribution of the vegetation phenology in the Qinling area (broadly) is closely related to elevation. From lowlands to highlands, the growing season start (GSS) was gradually delayed by 2 days/100 m, the growing season end (GSE) was gradually advanced by 1.9 days/100 m, and the growing season length (GSL) was gradually shortened by 3.9 days/100 m.

However, the increase in temperature significantly differed between the northern (NSQM) and southern (SSQM) slopes of the QMs. Additionally, the distribution of the GS and its relationship with elevation also exhibited obvious geographical differentiation as well as also large NSQM-SSQM differences compared with the entire region. Therefore, in the QMs, where there is a lack of long-term sequential observational phenology data, what is the regularity of the spatial distribution of the GS? What are the differences in the trends of the change in GS between the NSQM and SSQM? What is the pattern of the relationship between the GS variation and elevation? What are the differences in the relationship of the variation in GS with elevation between the NSQM and SSQM?

This study uses the climatologically significant GS, which is climatic growing season (CGS), defines the GS at a time when the mean daily temperature is stability above (below) the threshold temperature in the spring (in the autumn). The basis of this alternative method is that the growth and development of plants in temperate regions are mainly controlled by temperature (Melillo et al. 1990; Hodges 1991; Chen 1995). The main objective of this study is to investigate the NSQM-SSQM differences in relationship between the variation in the CGS and altitude over 31 years under global warming by transforming daily average temperature data from 32 meteorological stations in the QMs from 1985 to 2015 into regional spatial data through a spatial interpolation method. Our intention is to reveal the altitude effect and regional responses to warming in mountains, in order to provide a scientific theoretical basis for addressing climate change.

2 Study area

The QMs are a large mountain range that runs east-west across the central region of China. The QMs are an important geological dividing line in China that is consistent with the January 0 °C isotherm and the 800-mm annual precipitation line (Zhou et al. 2011). The mountains are the natural demarcation for five key physical geography elements, which are geology, climate, biology, water systems, and soil, as well as the dividing line between subtropical and warm temperate and moist and sub-humid climates. This striking function as an ecological barrier makes the QMs far more significant to China than other mountains, and they are key areas of terrestrial biodiversity with global significance (Yue and Xu 2014). The huge elevation differences are also a dominant factor in the formation of clear vertical climatic zones, soil zones, and biological population zones in the QMs. The mountain body is pitch-up in the north and pitch-down in the south, high in the west and low in the east. The NSQM is short and steep while the SSQM is long and gentle. Because the QMs have an enormous blocking effect on the northward warm moist airstream

from East Asia and the southward cold dry airstream, the climates differ substantially between the NSQM and SSQM. The north experiences droughts, whereas the south is humid. The NSQM has a warm-temperate, semi-humid and semi-arid climate, and the SSQM has a northern subtropical humid climate. The average temperature of the NSQM in January is lower than 0 °C, while the average temperature of the SSQM is higher than 0 °C. The study area focuses on a narrow portion of the QMs (Fig. 1), and in this paper, the dividing line is defined as the ridgeline.

3 Data and methods

3.1 Data sources

The daily average temperature data used for this study were collected at 32 national standard meteorological stations in the study area from 1985 to 2015 and obtained from the National Earth System Science Data Sharing Infrastructure (www.geodata.cn) and the Shaanxi Meteorological Bureau.

3.2 Methods of extracting CGS parameters

The GSS, GSE, and GSL are three important parameters used to characterize change in the CGS. The CGS used in the paper is defined by one of the typical climate indexes used by the Expert Team on Climate Change Detection and Indices (ETCCDI), which were originally proposed by the Commission for Climatology of the World Meteorological Organization (CCL-WMO) and the Climate and Ocean: Variability, Predictability, and Change (CLIVAR) project. That is (Peterson et al. 2001), the GSS is defined as the first day when the average daily temperature over 6 days is higher than 5 °C beginning on January 1 in the northern hemisphere (July 1 in the southern hemisphere), and the GSE is defined as the first day when the average daily temperature over 6 days is lower than 5 °C after July 1 in the northern hemisphere (January 1 in the southern hemisphere). The number of days between the GSS and GSE is the GSL.

3.3 Acquiring the spatial datasets of CGS parameters and verifying their accuracy

Based on the obtained GSS and GSE data, we selected co-kriging as the spatial interpolation method to transform the station data to area spatial data due to its high accuracy. The model used in this study was selected to comply with the standard optimal model and to calibrate the parameters with the following indicators in the prediction errors: the mean standardized nearest to 0, the root-mean-square minimum, the average standard errors closest to the root-mean-square, and the root-mean-square standardized closest to 1 (Tang and

Yang 2006). To guarantee the accuracy of the interpolated results for the mountainous region and to reflect the effects of topographic factors, a DEM (digital elevation model) was simultaneously treated as a covariate during the spatial interpolation process. Thus, the DEM was used to create the GSS and GSE gridded datasets for the QMs for each year from 1985 to 2015 (spatial resolution of 250 * 250 m and the WGS-1984-UTM-48 projection), and the GSL for the year was calculated from the difference between the GSE and GSS.

To verify the accuracy of the spatial interpolation results, this paper uses the daily mean temperature of seven regional alpine stations on Taibai Mountain (the highest peak in the QMs, altitude 3771.2 m) from 2013 to 2015 (Table 1). The same method was used to extract the GSS and GSE of each weather station as test data and to compare the corresponding to the station data from extracting the spatial interpolation results. The results showed that the average error from the seven stations was 2.06 days for GSS and 2.27 days for GSE, demonstrating that the difference between the spatial CGS parameters obtained by this method and the CGS parameters from the stations in the study area is relatively small. Therefore, the obtained spatial CGS parameters are of acceptable accuracy and reliability.

4 Results

4.1 Spatial distribution and trends in the change of the CGS

Figure 2 shows the spatial distribution of the CGS parameters in the QMs from 1985 to 2015. The spatial distribution pattern of the GSS, GSE, and GSL exhibited an altitudinal gradient.

The regional average GSS (Fig. 2a) ranged from the 35th to the 80th day of the year (DOY), but in the low-lying and flat part of the southernmost section of the study area, the GSS occurred before the 35th DOY while it occurred after the 80th DOY at higher altitudes. The GSS of the NSQM mainly occurred on the 50th–80th DOY, and for the SSQM, it mainly occurred on the 35th–80th DOY. The GSS in the low-lying and flat area in the middle part of the NSQM occurred before the 50th DOY, and it occurred before the 35th DOY in the low-lying area of the southern part of the SSQM. In some high-altitude areas of the NSQM and SSQM, the GSS occurred later than the 80th DOY. These results indicate that the GSS of the NSQM occurred approximately 15 days later than that of the SSQM. The trend of the annual change in the GSS (Fig. 2b) illustrated that the GSS of the NSQM and SSQM has been advancing over the past 31 years. The rate of the advance for the NSQM was 6.61 days/decade, and that of the SSQM was 5.39 days/decade. Thus, the rate of the advance in GSS of in the NSQM is larger than that of the SSQM.

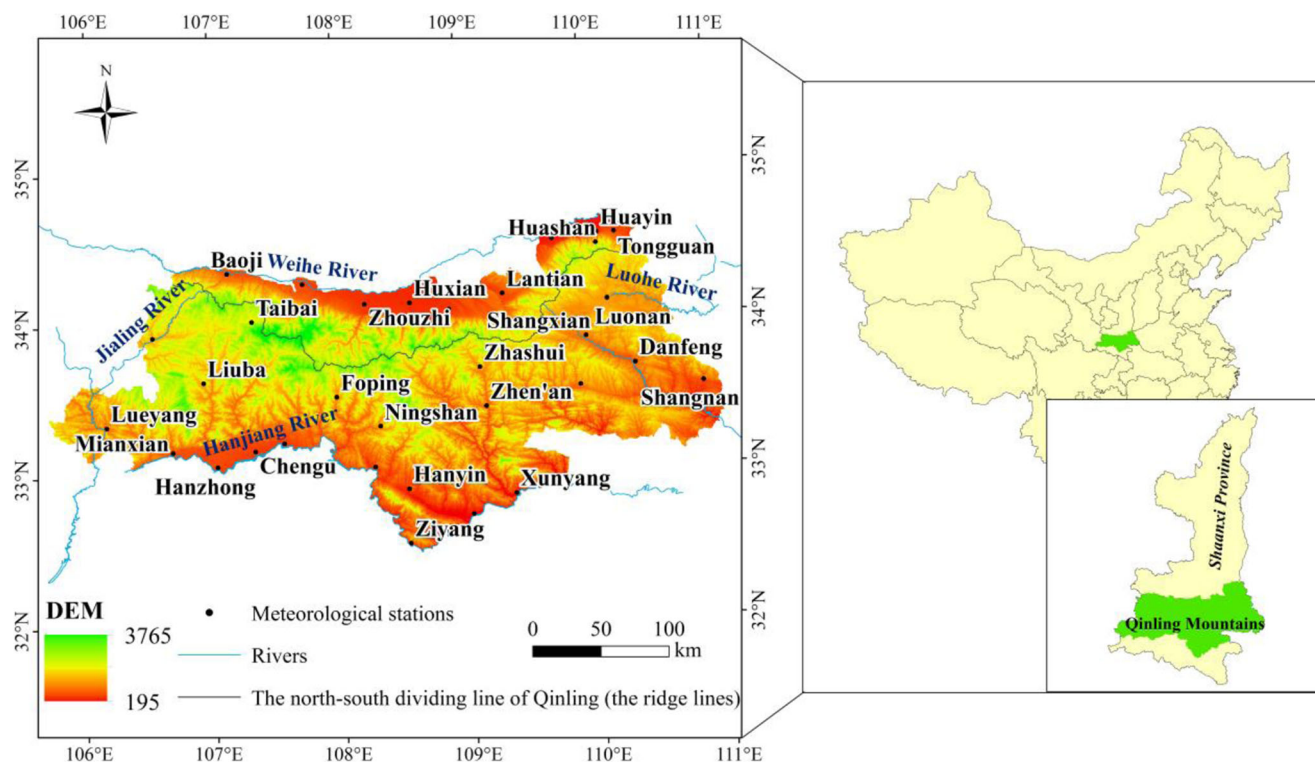


Fig. 1 Location of the study area and meteorological stations

The regional average GSE (Fig. 2c) ranged from the 315th to the 350th DOY, and it exhibited a distribution pattern along the altitudinal gradient. The GSE of the NSQM mainly occurred on the 315th to the 340th DOY, and for the SSQM, the GSE mainly occurred on the 315th to the 350th DOY. The spatial distribution of the GSE of the NSQM and SSQM also exhibited significant differences along the altitudinal gradient. This result indicates that the GSE of the SSQM was 10 days later than that of the NSQM. Over the past 31 years, the GSE of the NSQM and SSQM showed a delayed trend. The rate of delay for the NSQM was 1.31 days/decade, and that of the SSQM was 1.28 days/decade (Fig. 2d). Thus, there is little difference in the delay rate of the GSE between the NSQM and SSQM.

The regional average GSL (Fig. 2e) was concentrated at 230–320 days. The GSL of the NSQM was generally 230–295 days, and the GSL of the SSQM was generally 230–320 days. The GSL in the low-altitude area in the southern part of the SSQM was longer than 25 days, in contrast to the low-altitude area in the middle part of the NSQM. Over the

past 31 years, the GSLs of the NSQM and SSQM exhibited increasing trends. The rate of increase for the NSQM was 7.92 days/decade, and that in the SSQM was 6.66 days/decade (Fig. 2f). Thus, the rate of increase in the GSL of the NSQM is larger than that of the SSQM, mainly because the rate of advance of the GSS is larger for the NSQM than the SSQM, indicating that GSS advancement is the main reason for the extension in GSL.

4.2 Change characteristics of the CGS along an altitudinal gradient

The relationship between the CGS parameters and altitude in the QMs from 1985 to 2015 (Fig. 3a–c) demonstrates that the GSS, GSE, and GSL displayed regular changes with elevation, indicating a significant elevation sensitivity. With increasing altitude, the GSS was gradually postponed, the GSE was gradually advanced, and the GSL was gradually shortened. In the basins and plains at or below an elevation

Table 1 Regional meteorological stations on Taibai Mountain in the QMs

Location	Stations	Latitude (°)	Longitude (°)	Altitude (m)	Location	Stations	Latitude (°)	Longitude (°)	Altitude (m)
SSQM	Huangbaiyuan	33.82	107.52	1232	NSQM	Mei jiangongglu	34.07	107.47	1510
	Dayangongglu	33.88	107.41	2329		Honghegu	34.00	107.76	1273
	Dayangongglubei	33.97	107.30	2000		Yingge	34.08	107.68	857
	Dayangongglunan	33.87	107.46	1988					

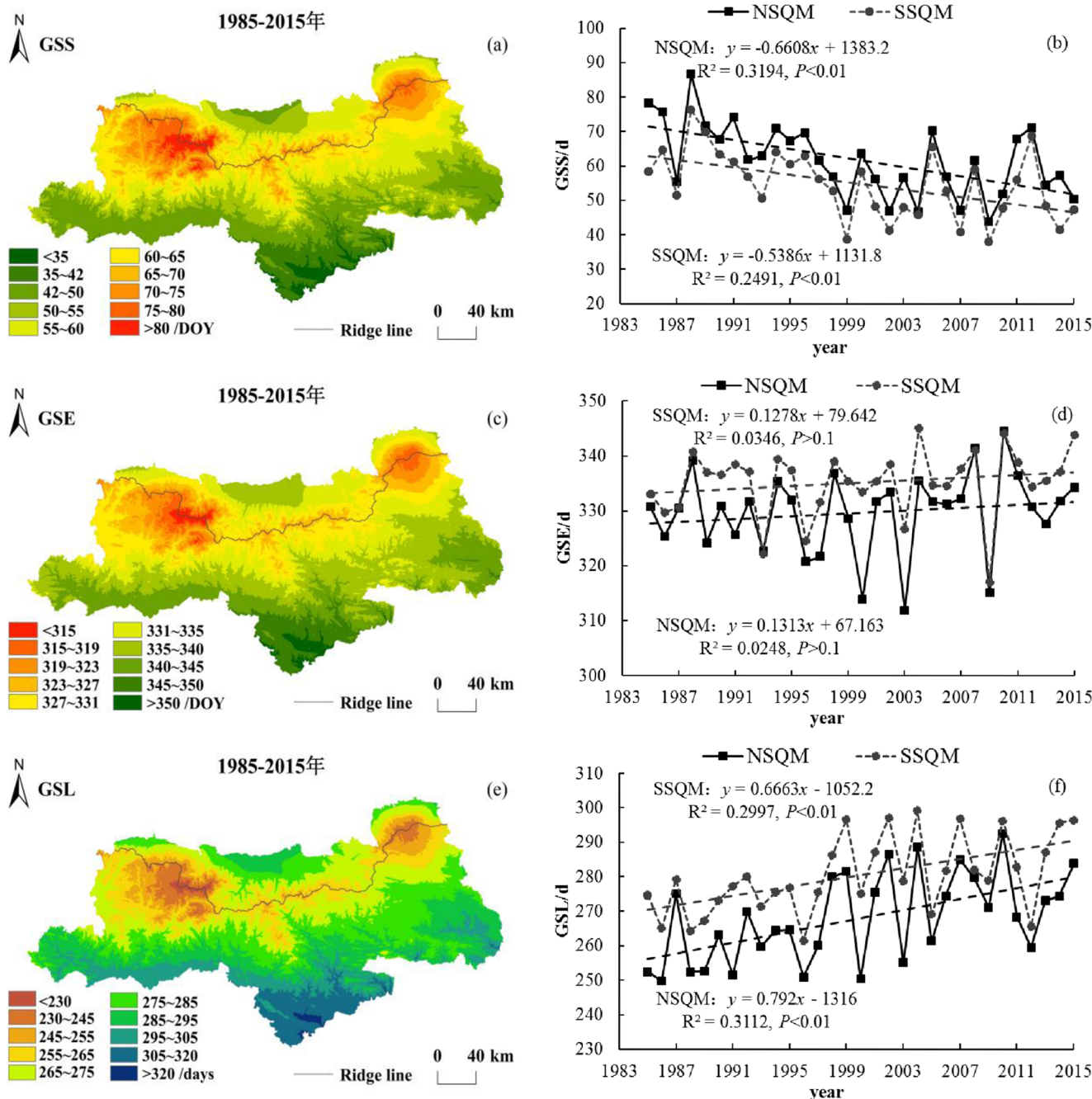


Fig. 2 Spatial distribution and trend of the annual change in CGS parameters in the QMs from 1985 to 2015

of 600 m, the fluctuations in the amplitude of the GSS, GSE, and GSL with altitude were larger, and the change rule is unclear. This result may be related to human activities; due to the urban heat island effect in the low-altitude region, warming in the low-altitude areas has significantly differed regionally. In the highland areas above 2700 m, the variation in the amplitudes of the GSS, GSE, and GSL with altitude was relatively more dramatic and was closely related to climatic conditions. The high-altitude areas are controlled by periglacial climate, low temperatures, and strong winds, and the mountaintop effect is obvious.

The relationship between the CGS parameters and elevation for the NSQM and SSQM from 1985 to 2015 (Fig. 3d–f) illustrates that the variation in the GSS, GSE, and GSL with altitude is greater for the SSQM than the NSQM. With an increase in altitude of 100 m in the NSQM, there is a delay in the GSS by 1.20 days, an advancement of the GSE by 0.79 days, and a shortening of the GSL by 1.99 days. For the SSQM, the GSS was delayed by 1.81 days, the GSE was advanced by 1.26 days, and the GSL was shortened by 3.07 days. These results are related to the differences in topography between the short, steep NSQM and the long, gentle

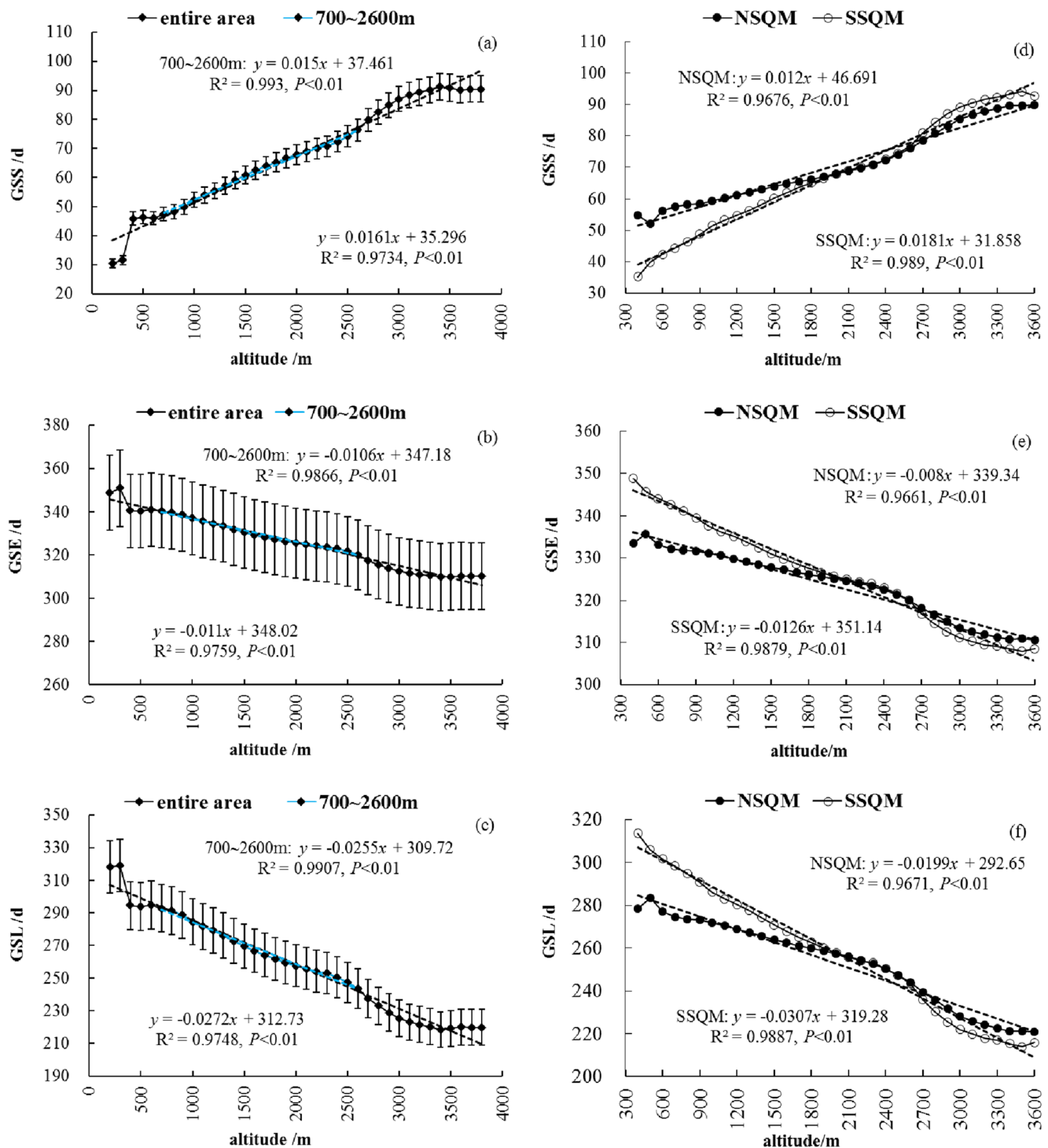


Fig. 3 Changing trends of the CGS parameters along altitude in the QMs from 1985 to 2015

SSQM. In the area below 1800 m in altitude, the GSS of the SSQM was earlier than that of the NSQM, the GSE of the SSQM was later than that of the NSQM, and the GSL of the SSQM was longer than that in the NSQM. These results are related to the higher temperatures of the SSQM compared to the NSQM. However, the opposite variation trend was observed in the high-altitude area above 2700 m. The GSS of the NSQM was earlier than that of the SSQM, the GSE of the

NSQM was later than that of the SSQM, and the GSL of the NSQM was longer than that of the SSQM. These results may be related to the existence of subsidence and a warm foehn wind effect on the leeward slope (NSQM). In the areas at altitudes of 1800~2700 m, there was little difference between the NSQM and the SSQM. With an incremental increase in altitude of 100 m, the ranges of the variation in the GSS, GSE, and GSL at three altitude gradients (≤ 1800 m, 1800~2700 m,

≥ 2700 m) demonstrated that the amplitudes of the delay in the GSS, the advancement of the GSE, and the extension of the GSL gradually narrowed (Table 2). Warming gradually increases with altitude, but in the NSQM, especially in its low-altitude area, there was a different trend, which may be related to the activities of the dense human population in the low-elevation area of the NSQM, where the warming amplitude is larger than that of the SSQM.

The elevation sensitivities of the GSS, GSE, and GSL of the NSQM and SSQM not only differ spatially but differ in their annual change trends as well. The relationship between the trend in the inter-annual change in the CGS parameters and altitude for the NSQM and SSQM during 1985–2015 (Fig. 4a–c) illustrated that the trends in the annual change of the advancing of the GSS, the delay of the GSE, and the extension of the GSL were significantly enhanced with an increase of elevation. Below an altitude of 1800 m, the trend of the inter-annual change in the GSS of the NSQM was relatively stable with a variation in elevation (-0.010 days/year·100 m $^{-1}$), while that of the SSQM gradually increased with the increase of elevation from being approximately 0 (-0.040 days/year·100 m $^{-1}$) until being convergence with the NSQM in the area at an altitude of 1800 m (both -0.66 days/year), and above an altitude of 1800, that of the NSQM and SSQM showed a significant strengthening in synchronization, especially in the area with an altitude above 2700 m (-0.057 , -0.055 days/year·100 m $^{-1}$ for the NSQM and SSQM, respectively). The trend of the inter-annual change in the GSE of the NSQM and SSQM displayed synchronization. The delayed trend in GSE was relatively slow with increasing altitude for the NSQM and SSQM below an altitude of 2700 m (both 0.019 days/year·100 m $^{-1}$). However, the postponed trends for the NSQM and SSQM were significantly enhanced, and the postponement amplitudes were not significantly different in the areas with an altitude above 2700 m (0.054, 0.052 days/year·100 m $^{-1}$ for the NSQM and SSQM, respectively). The trend of the inter-annual change in the GSL gradually lengthened with increasing altitude for the NSQM below an altitude of 2700 m (0.036 days/year·100 m $^{-1}$), but with an increase in altitude, the trend of the inter-annual change trend in the GSL of the SSQM gradually increased from being near to 0 (0.052 days/year·100 m $^{-1}$) and converged with that of the NSQM at an elevation of 2600 m (1.51 days/year). After this occurred, the extension trend of the GSL exhibited synchronous, rapid, and significant strengthening for the NSQM and SSQM (0.104 and 0.101 days/year·100 m $^{-1}$ in the NSQM and SSQM, respectively). This result may be because warming in the NSQM is more significant than warming in the SSQM. In addition, these results reflect that warming is significantly strengthened with an increase in altitude especially in the high-altitude areas.

Table 2 The range of the variation in the CGS parameters with an increase in altitude of 100 m at three altitude gradients

Altitude range/m	NSQM/day			SSQM/day		
	GSS	GSE	GSL	GSS	GSE	GSL
≤ 1800	0.89	0.60	1.50	2.02	1.47	3.49
1800–2600	1.26	0.76	2.02	1.37	0.85	2.22
≥ 2700	1.25	0.83	2.07	1.3	0.90	2.20

4.3 Spatial distribution and trends of the change in the CGS on the altitudinal vegetation belts

The vertical distribution of the vegetation in the QMs shows that there is a significant difference in the spectrums of the vertical vegetation zones between the NSQM and the SSQM. From low to high, the distribution of the vegetation of the NSQM is deciduous broad-leaved forests (600–1500 m), mixed coniferous and broad-leaved forests (1500–2400 m), coniferous forests (2400–3100 m), and alpine shrub meadow and deciduous coniferous forests (> 3100 m). The distribution of the vegetation of the SSQM is evergreen and deciduous broadleaved mixed forest (600–1300 m), conifer and broad-leaf mixed forest (1300–2200 m), coniferous forest (2200–3000 m), and alpine shrub meadow (> 3000 m). Due to the differences in the climatic conditions between the NSQM and SSQM, the two sides of the ridge exhibited landscape differences; the north side of the ridge is covered by trees, and the south is covered by grass. Based on the above, the spatial distribution range of the vertical vegetation belts on the NSQM and SSQM is shown in Fig. 5a. According to this, the variation in the characteristics of the GSS, GSE, and GSL among the different vegetation vertical belts are further analyzed.

The mean values of the GSS, GSE, and GSL for different vertical vegetation belts (Table 3) demonstrated that, from low altitude to high altitude, the GSSs were gradually delayed for both the NSQM and SSQM and occurred earlier on the SSQM, but the GSS of the NSQM was approximately 2.83 days earlier than that of the SSQM in the alpine meadow area. The GSEs were gradually advanced for the NSQM and SSQM and occurred later on the SSQM, but in the alpine meadow area, the GSE was approximately 1.77 days later for the NSQM than the SSQM. The GSLs of in both the NSQM and SSQM were gradually shortened, and the duration of the GSL was longer for the SSQM than the NSQM. In the alpine meadow area, by contrast, the GSL was approximately 4.63 days longer for the NSQM than the SSQM. From these results, it can be seen that the occurrence of the GSS and GSE and the duration of GSL in the alpine meadow area were reversed for the NSQM and SSQM.

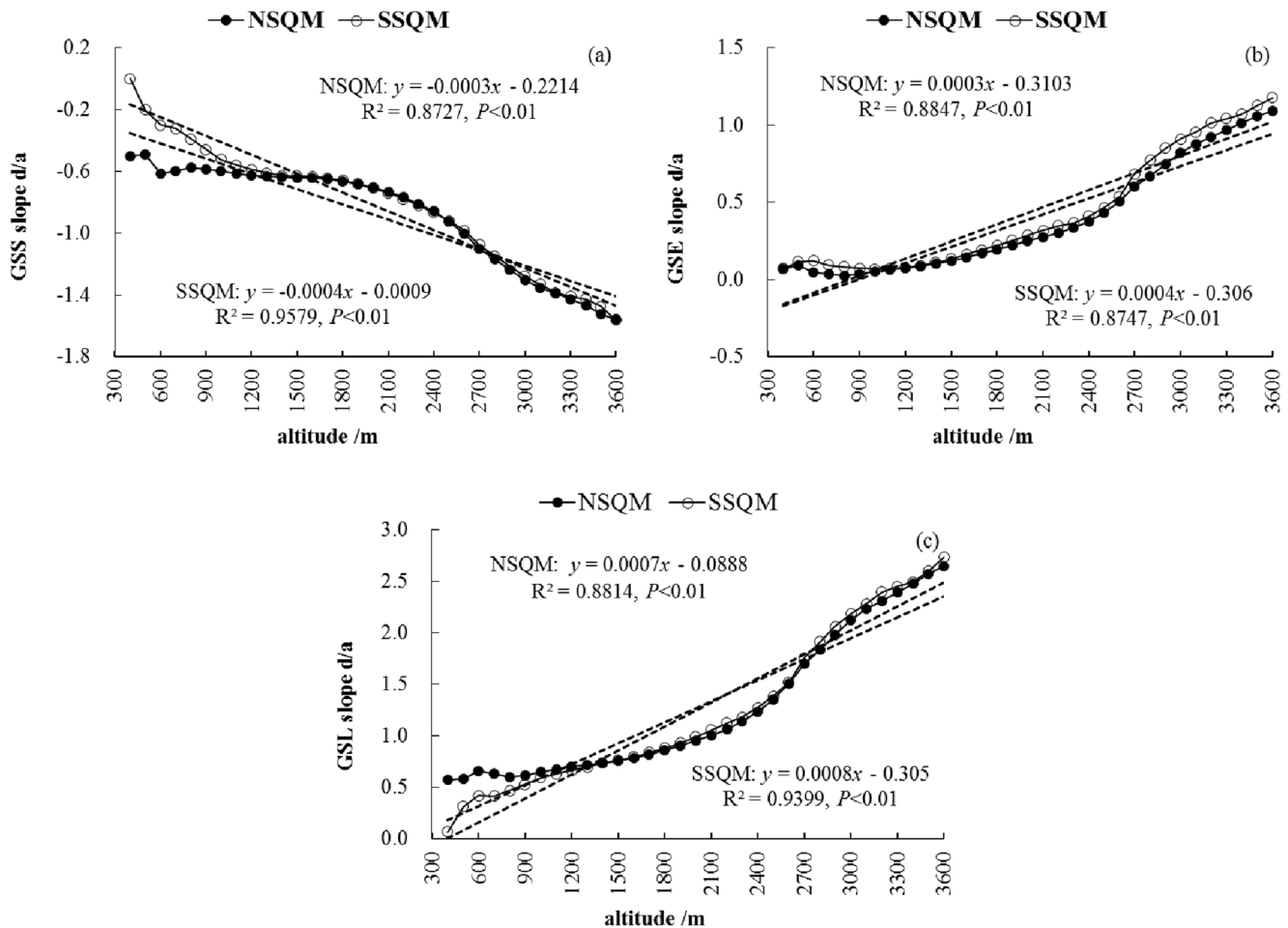


Fig. 4 Trends in the annual change in the CGS parameters along altitude for the NSQM and SSQM from 1985 to 2015

The slope of the inter-annual variation in the CGS parameters for the different vertical vegetation belts of the NSQM and SSQM from 1985 to 2015 (Fig. 5b–d) demonstrates that the trend in the inter-annual variation in the GSS, GSE, and GSL obviously differed among the belts. With an increasing elevation gradient, the trends of the inter-annual change in the advance of the GSS, the delay of the GSE, and the extension of the GSL were gradually strengthened in the vertical vegetation belts of the NSQM and SSQM; specifically, the GSS, GSE, and GSL of the NSQM and SSQM were largest in the alpine meadow area. In each vertical vegetation belt, the amplitudes of the advance in the GSS of the NSQM were not more obvious than that of the SSQM, the amplitudes of the delay in the GSE of the NSQM and SSQM were not substantially different, and the extension of the GSL of the NSQM was more obvious than that of the SSQM. The amplitudes of the change in GSS and GSL exhibited the largest differences in the vegetation belt at an altitude ≤ 600 m; then, the range in the variation along the vertical vegetation belt of the NSQM and SSQM gradually converged with increasing elevation.

5 Discussion and conclusions

5.1 Conclusions

In this study, we found that the spatial distribution patterns of the GSS, GSE, and GSL followed an altitudinal gradient. The GSS mainly occurred on the 50th–80th DOY for the NSQM and on the 35th–80th DOY for the SSQM. The GSE mainly occurred on the 315th–340th DOY for the NSQM and on the 315–350th DOY for the SSQM. The GSL was concentrated within 230–295 days for the NSQM and 230–320 days for the SSQM. Over the past 31 years, the rate of the advance in the GSS of the NSQM (6.61 days/decade) was higher than that of the SSQM (5.39 days/decade). The rate of the delay in the GSE of the NSQM (1.31 days/decade) was greater than that of the SSQM (1.28 days/decade). The rate of the extension in the GSL of the NSQM (7.92 days/decade) was greater than that of the SSQM (6.66 days/decade).

The GSS, GSE, and GSL exhibited significant sensitivities in elevation with increases in altitude. For each 100 m increase in altitude for the NSQM, the GSS was postponed by 1.20 days, the GSE was advanced by 0.79 days, and the

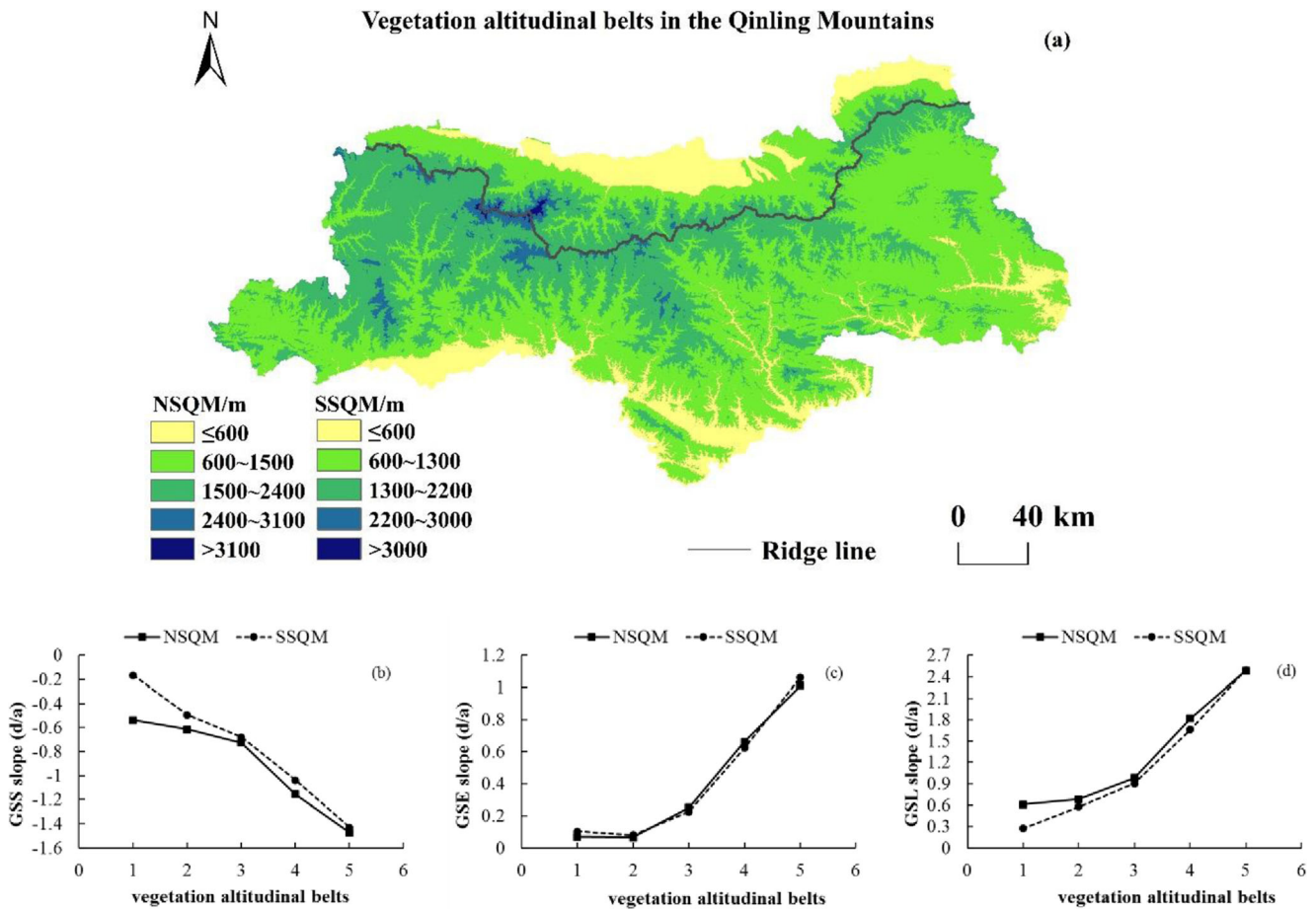


Fig. 5 Altitudinal gradient of the vertical vegetation belts and the trends of the inter-annual change in the CGS parameters of the NSQM and SSQM

GSL was shortened by 1.99 days; for the SSQM, the GSS was postponed by 1.81 days, the GSE was advanced by 1.26 days, and the GSL was shortened by 3.07 days. In the area where the altitude was below 1800 m, the GSS of the SSQM was earlier than that of the NSQM, the GSE of the SSQM was later than that of the NSQM, and the GSL of the SSQM was longer than that of the NSQM. However, the trends of the change in the GSS, GSE, and GSL were opposite in the area at an altitude above 2700 m, and the GSS, GSE, and GSL were not substantially different between the NSQM and SSQM in the high-altitude area of 1800~2700 m.

The trends of the inter-annual change trends in the GSS, GSE, and GSL also displayed significant elevational sensitivity. The trends of the inter-annual variation in the advanced GSS, postponed GSE, and extended GSL of the NSQM and SSQM were significantly strengthened with increasing elevation, especially in the areas with an altitude above 2700 m. In areas with an altitude below 1800 m, the trend of the inter-annual variation in the GSS of the NSQM was relatively stable with elevation, while the GSS of the SSQM gradually increased from approximately 0. The trends of the inter-annual variation trends in the GSE of the NSQM and SSQM exhibited synchrony, and the delayed tendency of the GSE of the

Table 3 Mean CGS parameters in the vertical vegetation belts

NUM	Altitude ranges (m)	The NSQM (day)			Altitude ranges (m)	The SSQM (day)		
		GSS	GSE	GSL		GSS	GSE	GSL
1	≤ 600 m	53.95	334.44	280.49	≤ 600 m	40.17	345.52	305.35
2	600~1500 m	60.45	330.28	269.82	600~1300 m	51.46	337.56	286.10
3	1500~2400 m	67.16	325.57	258.41	1300~2200 m	62.74	329.26	266.52
4	2400~3100 m	78.26	318.44	240.18	2200~3000 m	74.30	321.62	247.32
5	> 3100 m	88.90	311.24	222.37	> 3000 m	91.73	309.47	217.74

NSQM and SSQM was relatively slow in the areas below 2700 m in elevation. The trends in the inter-annual variability of the GSL exhibited a slight lengthening with elevation for the NSQM, while for the SSQM, the GSL gradually increased from approximately 0 and converged with the tendency of the NSQM to extend in areas above 2600 m in elevation.

The mean GSS, GSE, GSL and their inter-annual change trends exhibited obvious differences with altitudinal gradient in the varied vertical vegetation belts. Among the different vertical vegetation belts from low-altitude to high-altitude areas, the occurrence of the GSS and GSE and the duration of the GSL were all exchanged in the alpine meadow area of the NSQM and SSQM, with trends indicating that the GSS of the NSQM was earlier than that of the SSQM, the GSE of the NSQM was later than that of the SSQM, and the GSL of the NSQM was longer than that of the SSQM. The strength of the trends of the inter-annual change in the GSS, GSE, and GSL in different vertical vegetation belts gradually increased with elevation, and the amplitude of the variation was largest in the alpine meadow area of the NSQM and SSQM. Except for the smaller variation amplitude of the GSE of the NSQM and SSQM, the differences in the GSS and GSL of the vegetation belts at altitudes of ≤ 600 m were largest, and the ranges in the variation for the NSQM and SSQM gradually converged with an increase in elevation.

5.2 Discussion

Due to the unique geographical location and topographical features of the QMs, their regional response to climate change is typical and representative. The warming of this climate-sensitive areas can be regarded as an early warning signal for climate change in China and even globally.

The spatial and temporal changes in the CGS parameters in the QMs revealed the elevational effect of mountain warming. On the one hand, the spatial distribution of the GSS, GSE, and GSL as well as their trends in inter-annual variability displayed differences related to the variations in the climate conditions and warming trends with changing elevation on the NSQM and SSQM. On the other hand, in the high-altitude area, especially at altitudes ≥ 2700 m in the QMs, the ranges of the variation in the GSS, GSL, and GSE reversed for the NSQM and SSQM, and the inter-annual change trend was significantly enhanced, demonstrating the elevation dependence and sensitivity of high-altitude areas to warming. Our research found that an altitude of 2700 m in the QMs is an important dividing line for the response to climate change with altitude. This altitude is nearly consistent with the height of the alpine timberline in the QMs. However, due to the lack of meteorological stations and phenological observation sites, it is difficult to verify the warming response in terms of the relationship between altitude and phenological changes in the high-altitude areas (Chen et al. 2015; Piao et al. 2011; Shen

et al. 2014). Therefore, the relevant mechanisms require further study. In addition, it is important to consider what causes the greater warming at higher altitudes. Some scholars believe that it may be the result of the intensified feedback effect of the reflectivity of snow and ice in high-altitude areas during global warming (Giorgi et al. 1997; Fyfe and Flato 1999; Liu and Hou 1998), but others think that the warming in high-altitude areas may be related to cloudiness (Chen et al. 2003) or heating by aerosol absorption (Ramanathan et al. 2007). Relating warming to a physical mechanism requires more in-depth observation and numerical simulation analysis.

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