



Spatiotemporal differences in the climatic growing season in the Qinling Mountains of China under the influence of global warming from 1964 to 2015

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Abstract

Based on daily mean temperature data from 32 meteorological stations in the Qinling Mountains (QMs) of China, we analyzed the characteristics and differences of the spatiotemporal changes in the climatic growing season (CGS) in the QMs from 1964 to 2015. Our results are as follows. First, over the past 52 years, the temperature of the QMs significantly increased at a mean rate of 0.22 °C/decade ($P < 0.01$) in over 98.04% of the area. Significant north–south spatial differences were observed in temperature changes; also, significant differences in the temperature changing trends were observed before and after the abrupt change in temperature. Second, the spatial distributions of the mean growing season start (GSS), end (GSE), and length (GSL) in the QMs varied based on regional differences in latitude and topography. Notably, the GSS, GSE, and GSL were gradually delayed, advanced, and shortened, respectively, as latitude and elevation increased. After the abrupt change in temperature, whether it is in the NSQM (northern slopes of the QMs) or the SSQM (southern slopes of the QMs), the GSS, GSE, and GSL expanded into high-elevation areas. Third, over the past 52 years, the GSS in the QMs exhibited a significant advancing trend of 2.7 days/decade, the GSE was delayed at a rate of 0.66 days/decade, and the GSL displayed a significant extension of 3.36 days/decade. Before the abrupt change in temperature, the GSS, GSE, and GSL exhibited non-significant changing trends; however, the trends in the GSS, GSE, and GSL were more significant after the abrupt change than before. Fourth, the GSS, GSE, and GSL trends in the QMs were significantly different in the NSQM and SSQM regions. After the abrupt change, the GSS, GSE, and GSL trends along the NSQM were more significant than those along the SSQM.

1 Introduction

Global warming is an indisputable fact. The fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC 2013) noted that over the past 130 years (from 1880 to 2012), the global temperature has risen by 0.85 °C and the

rate of the average surface temperature increase was 0.12 °C/decade from 1951 to 2012. Therefore, the last 30 years (from 1983 to 2012) was likely the hottest period in history (IPCC 2013; Qin and Thomas 2014). Over the past 50 years (from 1951 to 2007), the surface temperature of China has risen rapidly at a rate of 0.23 °C/decade (Ren et al. 2012). Warming accelerated in the 1980s (Ren et al. 2005). Climate warming has a strong impact on ecosystems and can cause natural processes of ecosystems and vegetation communities to change in composition, structure, spatial pattern, and function (IPCC 2007a, b). The growing season (GS) is defined as “the number of days a plant can grow in a year” (Wang 1963), which is an important control factor for ecosystem functions. Changes in the GS can sensitively reflect the response of a terrestrial ecosystem to climate change, and such changes have become important indicators of climate change (Linderholm et al. 2008; Song et al. 2010).

Many studies have reported that the GS has undergone significant changes with climate warming in many parts of

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the world (Parmesan and Yohe 2003; Linderholm 2006; IPCC 2007a, b). In recent years, scholars have analyzed changes in the GS through phenological observations (Chmielewski and Rölzer 2002; Cleland et al. 2007; Dai et al. 2013), vegetation indexes based on remote sensing (Karlsen et al. 2009; Jeong et al. 2011; Jochner et al. 2012), and meteorological observations (Robeson 2002; Linderholm et al. 2008; Song et al. 2010) that reflect the effects of climate change on the GS. Studies have shown that in different countries and regions in the northern hemisphere (e.g., Germany, the USA, China, Japan, and Republic of Korea), spring phenology advances, autumn phenology delays, and extended GS periods have occurred (Parmesan 2007; Gordo and Sanz 2009; Chen and Xu 2012). Several studies have analyzed the effects of temperature on plant phenology, and according to the data from the IPG (International Phenology Garden), if the temperature in Europe in early spring rises by 1 °C, the GS begins 7 days earlier than normal, and if the annual average temperature increases by 1 °C, it will cause the GS to lengthen by 5 days (Chmielewski and Rölzer 2001). Plant phenology data from Germany suggested that when the temperature rises by 1° in spring, the phenophase will advance by 2.5–6.7 days, the GS will lengthen by 2.4–3.5 days, and the autumn phenology will be affected (Menzel 2003). In China, Zhang (1995) demonstrated that temperature was a major factor that could affect the changes in plant phenology. Chen and Lin (2012) suggested that the start date of the spring GS was advanced by 3.1 days and the end date of the autumn GS was delayed by 2.6 days when the average daily temperature increased by 1 °C in temperate regions of China. Zhang et al. (2005) believed that the advancement and delay of the phenophase were non-linear in response to an increase or decrease in temperature. Some scholars have found that temperature changes with latitude, longitude, and elevation can also lead to changes in phenology (Hopkins 1918; Walther et al. 2002).

Mountains are areas that are sensitively affected by global climate change. As a natural symbol of Chinese geography, the Qinling Mountains (QMs) are the geographical boundary of North and South China, the demarcation line of Chinese climate, the transition zone and sensitive areas in the central region of China's ecological environment, and a sensitive area of the regional response to climate change (Bai et al. 2012; Liu and Shao 2000). For nearly half a century, the temperature in the QMs has been increasing, especially since the 1980s (Bai 2014). Because long-term phenological data from observations and remote sensing are comparatively scarce, this study uses the climatologically significant GS, or the CGS, which is based on the mean daily temperature as an indicator to define the GS with its 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). Based on mean daily temperature data from

32 national meteorological stations in the QM area and the spatial interpolation method, this paper analyzes the following questions. In the context of global warming, how has the temperature changed in the QMs over the past 52 years? Additionally, how has the CGS changed? What are the differences in the CGS before and after the abrupt change in temperature? What are the differences in the CGS along the northern and southern slopes of the QMs (NSQM and SSQM, respectively)? The focus of this paper is to determine the trends of CGS change in the QMs, which can contribute to analyzing the response of the QM terrestrial ecosystem to climate change and the evolution of climate in the future to provide a scientific and theoretical basis for coping with climate change.

2 Study area

The QMs are the highest mountain along the east–west direction in the central region of China. Due to their location and elevation, the QMs are unique. The dividing line of the QMs is basically consistent with the 0 °C isotherm in January and the 800-mm annual precipitation line (Zhou et al. 2011). The mountains are known as “China's backbone” and are the important geographical dividing line between South and North China. Specifically, they are also the climate transition belt in China where the typical subtropical zone changes gradually toward the warm temperate zone and the humid zone changes gradually toward the semi-humid zone. This obvious demarcation has made its significance to China far beyond the ordinary mountains, and the QMs have been listed as a key area of terrestrial biodiversity of global significance (Yue and Xu 2014). The NSQM is short and steep, and the SSQM is long and gradual. Mount Taibai is the main and highest peak in the QMs. Mount Hua on the NSQM is one of China's five sacred mountains, and it is well known for its abrupt cliffs. The climate difference between the NSQM and SSQM is obvious, with a dry climate to the south and a moist climate to the north. The NSQM is characterized by a warm temperate zone (i.e., semi-humid and semi-arid climate), and the SSQM has a northern subtropical humid climate. There is a large difference in winter temperatures between the NSQM and SSQM. The annual temperature in January along the NSQM is below 0 °C, and the temperature is above 0 °C in January along the SSQM. The study focuses on a specific area in the QMs (Fig. 1). The dividing line noted in this paper is created by the ridgeline of the QMs.

3 Data and methods

3.1 Data sources and processing

Daily mean temperature data collected at 32 national meteorological stations in the study area from 1964 to 2015 were

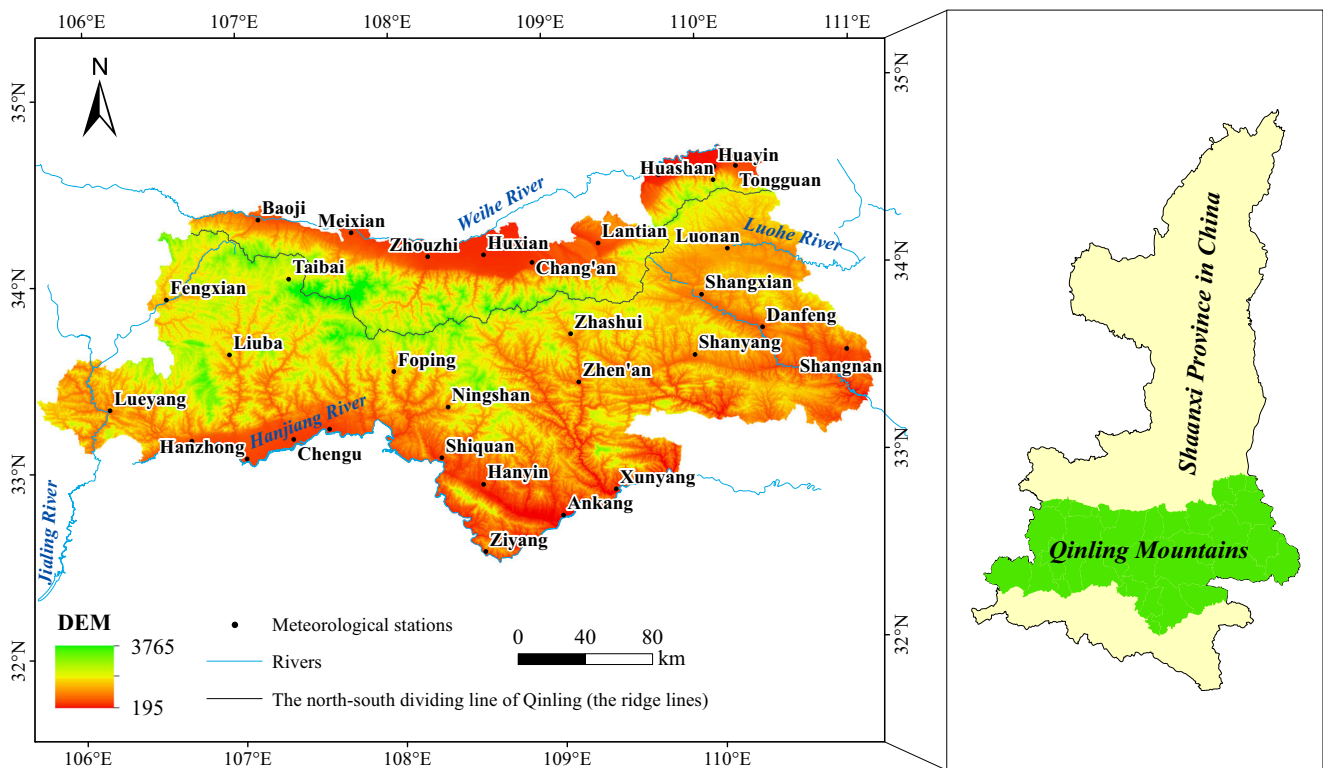


Fig. 1 Location of the study area and meteorological stations

obtained from the National Earth System Science Data Sharing Infrastructure (www.geodata.cn) and the Shaanxi Meteorological Bureau.

The GS used in the paper is defined by one of the typical climate indexes used by the ETCCDI, which were originally proposed by the WMO-CCL and the CLIVAR (Peterson et al. 2001), and the CGS parameters used in the study are shown in Table 1. Beginning on January 1 (July 1) in the northern (southern) hemisphere, the growing season start (GSS) is defined as the first day when the average daily temperature over 6 days is higher than 5 °C. After July 1 (January 1 in the southern hemisphere), the growing season end (GSE) is defined as the first day when the average daily temperature over 6 days is lower than 5 °C. The number of days between the GSS and GSE is the growing season length (GSL). The GSS, GSE, and GSL are three important parameters used to characterize changes in the CGS.

Based on the GSS and GSE station data, after accuracy verification, we selected co-kriging as the spatial interpolation

method due to its high accuracy. This space interpolation method can transform station data to area data. To guarantee the accuracy of the interpolated results in the mountainous region and reflect the effects of topographic factors, a digital elevation model (DEM) was treated as a covariate during the spatial interpolation process. Notably, the DEM was used to establish the gridded datasets of GSS and GSE for the QMs in each year from 1964 to 2015 by taking the annual difference between the GSE and GSS and using the GSL of the most current year. The spatial resolution was 250 × 250 m, and the projection was WGS-1984-UTM-Zone-48.

3.2 Methods

The climate tendency rate can indicate the direction and speed of changes in a sequence of climate factors; therefore, we utilized the method to analyze long-term trends in temperature in the grid. Its expression is as follows:

$$slope = \frac{n \sum_{i=1}^n ix_i - \sum_{i=1}^n i \sum_{i=1}^n x_i}{n \sum_{i=1}^n i^2 - \left(\sum_{i=1}^n i\right)^2} \tag{1}$$

Where slope is the value of the climate tendency rate, n is a given time series (year, $n = 1, 2, 3, \dots$), x_i is the element value of the i th year x . When slope > 0 or slope < 0, it indicates that x

Table 1 CGS parameters used in the study

CGS parameters	Start date	Definition
GSS	Beginning on January 1	6 days with daily $T_{mean} > 5\text{ °C}$
GSE	Beginning on July 1	6 days with daily $T_{mean} < 5\text{ °C}$
GSL	–	GSE–GSS

increases or decreases with time; slope $\times 10$ is called the climate tendency rate every 10 years ($^{\circ}\text{C}/10\text{a}$).

The climate trend coefficient can reflect the direction and degree of long-term changes in the CGS parameters. Therefore, we utilized the method to analyze long-term trends in the CGS parameters in the grid. Its expression is as follows:

$$r_{xt} = \frac{\sum_{i=1}^n (x_i - \bar{x})(i - \bar{i})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (i - \bar{i})^2}} \quad (2)$$

Where r_{xt} is the correlation coefficient between the value of the CGS parameter sequence of n times (year) and the natural sequence 1,2,3..., n , n is the sample size (years), x_i is the CGS parameter value of the i th year, \bar{x} is the mean value of the CGS parameter n years, and \bar{i} is the sample mean, $\bar{i} = (n + 1)/2$. When $r_{xt} > 0$ or $r_{xt} < 0$, it indicates that x has a linear increase or decrease trend during the calculated n years.

Moreover, the t test was used to assess the significance of each trend. The variable of r_{xt} follows the t distribution. The degree of freedom is $n - 2$. It is defined as:

$$t = (r_{xt} \sqrt{n-2}) / \sqrt{1-r_{xt}^2} \quad (3)$$

Accordingly, the results were divided into 4-class grades based on the t values: highly significant ($P \leq 0.01$), significant

($0.01 < P \leq 0.05$), weakly significant ($0.05 < P \leq 0.1$), and non-significant ($P > 0.1$) changes.

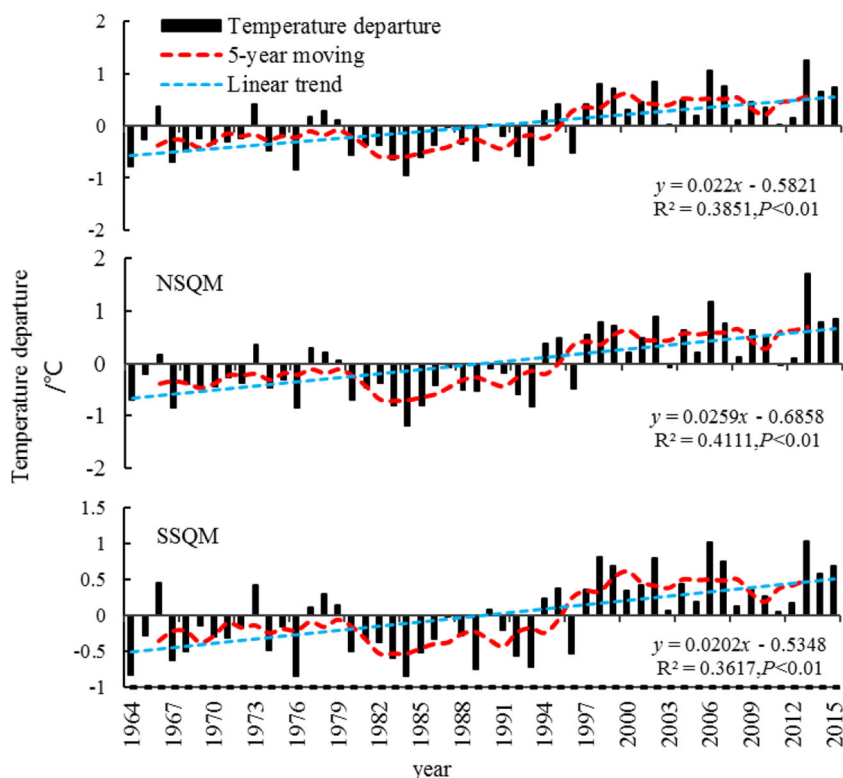
4 Results

4.1 The temperature spatial distribution and trends in the QMs

4.1.1 The abrupt change of the temperature during 1964–2015

The departure changes of annual temperature in the QMs from 1964 to 2015 are shown in Fig. 2. This shows that the temperature warming in the QMs mainly occurred over the past 30 years and the temperature variations can be characterized by abrupt changes. Warming mainly began in the mid-1980s. Specifically, the entire QM region and the NSQM and SSQM areas experienced simultaneous temperature variations, with an abrupt change in 1984 and a steady upward trend that began in 1985 (Deng et al. 2017). This trend was consistent with the conclusions of previous studies, which observed the abrupt change that occurred in China in 1984 (Wang et al. 2010; Ding et al. 2007; Ren et al. 2005). This study uses 1985 as the year of the abrupt temperature change in the QMs.

Fig. 2 Departure changes of annual temperature in the QMs during 1964–2015



4.1.2 The temperature spatial distribution and trends during 1964–2015

The spatial distribution of the annual mean temperature in the QMs and temperature changes were obtained by creating a temperature raster dataset (Zhai et al. 2016) from 1964 to 2015 (Fig. 3a, b). The average annual temperature range in the QMs was from -3.28 to 16.10 °C, with ranges between -3.28 and 14.46 °C in the NSQM region and -1.83 and 16.10 °C in the SSQM region. Temperature changes in the QMs exhibited

obvious spatial differences. Specifically, temperatures in the low-elevation areas and valleys of the NSQM and SSQM were high, and temperatures in the high-elevation areas near the ridgeline were low. The rate of temperature increase in the QMs was 0.22 °C/decade, with rates of 0.24 and 0.21 °C/decade in the NSQM and SSQM regions. The results of the *t* test showed that 98.04% of the QM area experienced a significant temperature increase ($P \leq 0.05$) over the past 52 years. Additionally, 99.46% of the NSQM area and 89.70% of the SSQM area exhibited increasing trends ($P \leq 0.01$).

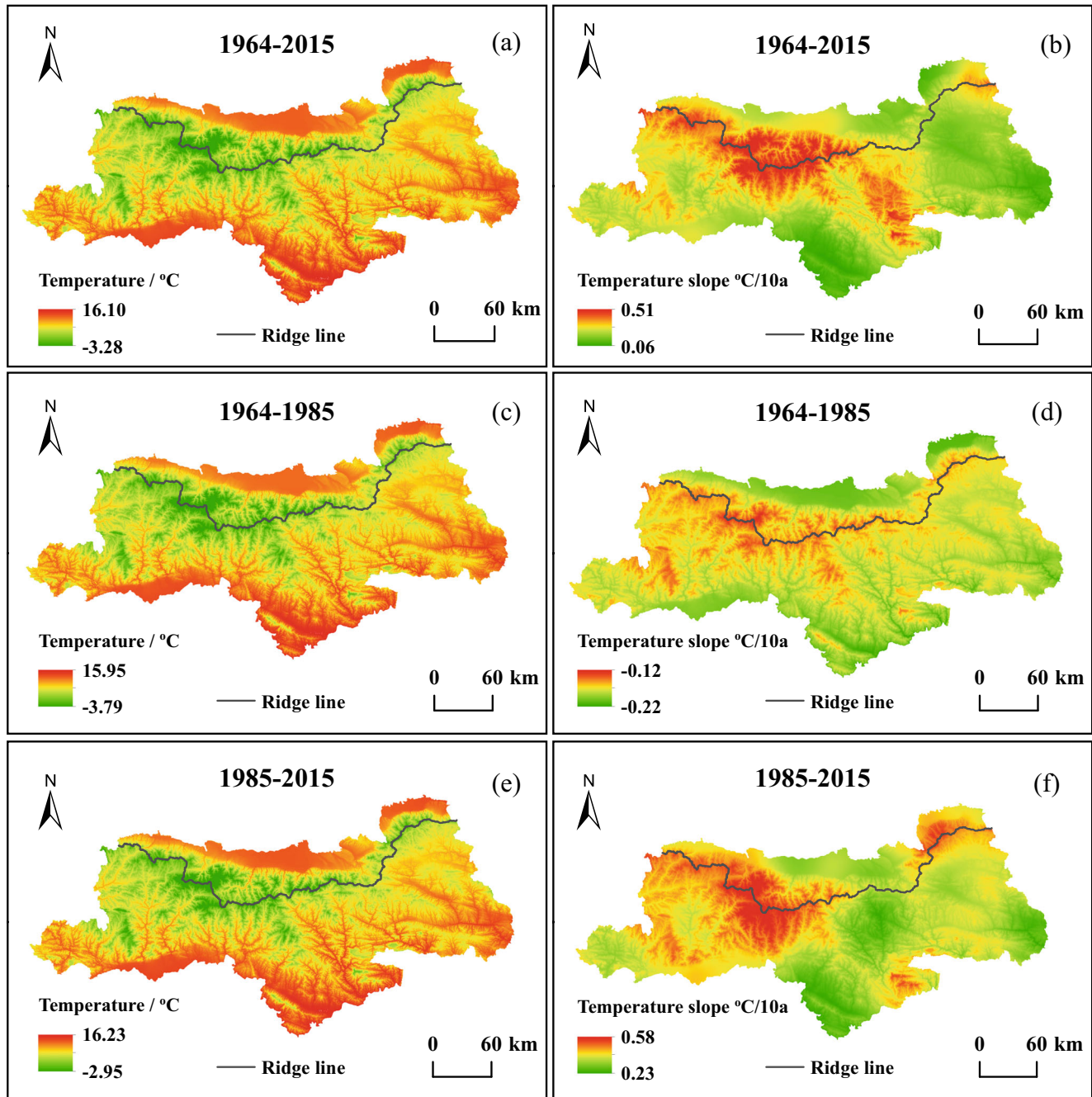


Fig. 3 Spatial distribution of the annual mean temperature and the associated trend in the QMs during 1964–2015

The spatial distribution of the annual mean temperature in the QMs and temperature changes before and after the abrupt change are presented in Fig. 3c–f). Before the abrupt change, the rate of temperature change in the QMs was small, with an average annual temperature warming rate of -0.17 °C/decade in the entire area, a rate of -0.18 °C/decade in the NSQM area, and a rate of -0.17 °C/decade in the SSQM area. Only 3.32% of the region exhibited a significant ($P \leq 0.05$) upward trend in temperature. After the abrupt change, the temperature increase in the QMs was especially significant. Notably, the average annual temperature increased by 0.37 °C/decade, including rates of 0.39 and 0.36 °C/decade in the NSQM and SSQM areas, respectively. The warming amplitude for the entire QM was significant, with warming observed in 99.76% and 98.54% of the NSQM and SSQM areas, respectively. These results indicate that after the abrupt change, the warming trend in the QMs was more significant than that before the abrupt change, and the warming trend was more significant in the NSQM area than in the SSQM area.

4.2 The CGS spatial distribution and trends in the QMs

4.2.1 The CGS spatial distribution during 1964–2015

The spatial changes in the CGS parameters in the QMs were analyzed from 1964 to 2015 (Fig. 4). The GSS in the QM area mainly occurred on the 40th–80th day of the year over the past 52 years; however, the GSS was before the 40th day in the low-lying areas of the SSQM, and the GSS was after the 80th day in some areas with high elevations and latitudes. The GSE mainly occurred between the 319th and 345th days, based on elevation and latitude differences. The GSL was 250–300 days. The occurrence of the GSS along the NSQM was later than that along the SSQM, and the occurrence of the GSE along the SSQM was later than that along the NSQM. Additionally, the GSL along the NSQM was shorter than that along the SSQM. However, the varying spatial characteristics of these three parameters were consistent. Specifically, the GSS was gradually delayed, the GSE gradually advanced, and the GSL gradually shortened as latitude and elevation increased. Further analysis of the changes in low-elevation areas (below 600 m) suggested that for an increase of 1° in

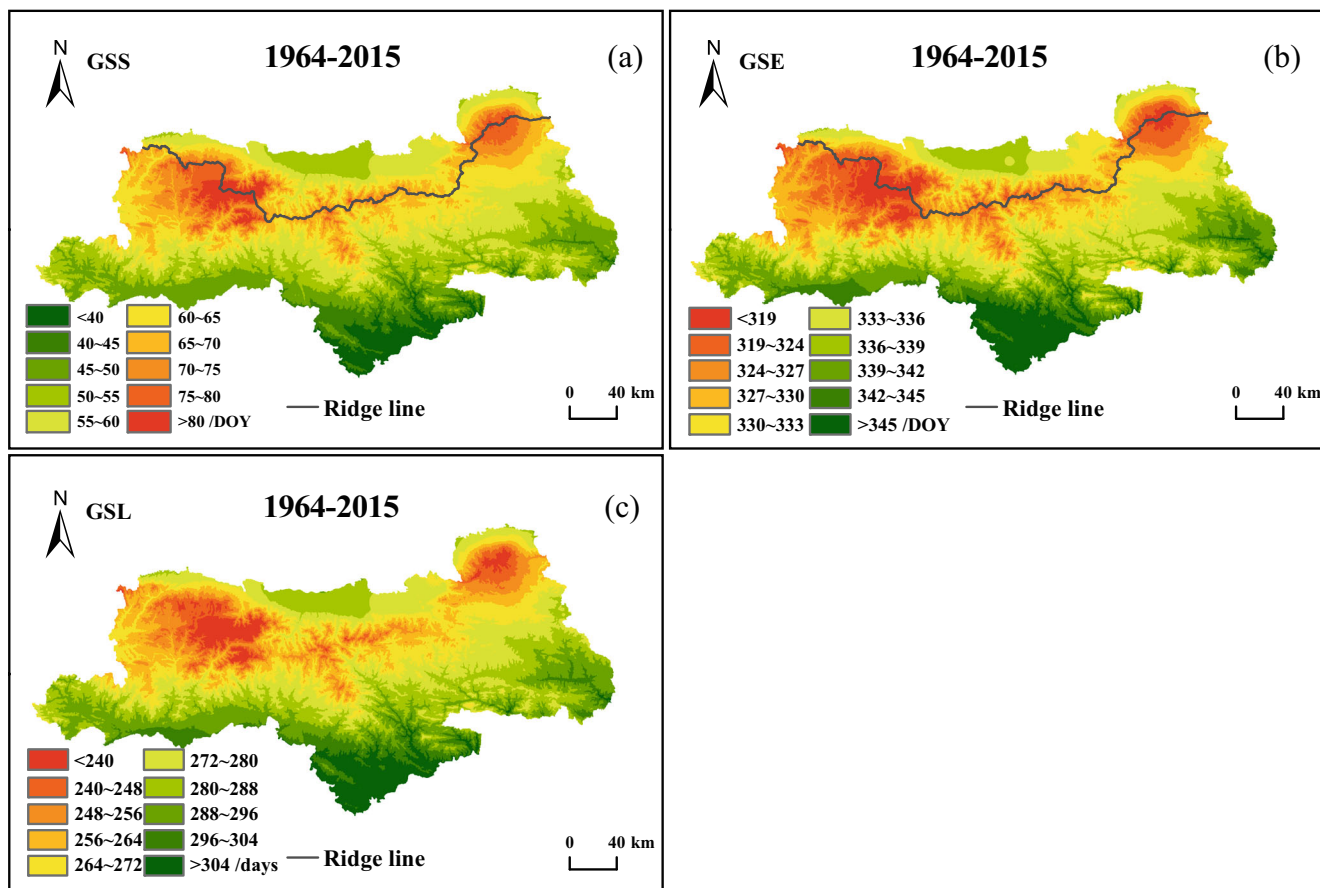


Fig. 4 Spatial distribution of the CGS parameters in the QMs during 1964–2015

latitude, the GSS along the NSQM was delayed by 6.86 days, the GSE advanced by 5.43 days, and the GSL shortened by 12.29 days, and along the SSQM, the GSS was delayed by 12.71 days, the GSE advanced by 8.84 days, and the GSL was shortened by 21.55 days. In terms of elevation, an increase of 100 m resulted in a delay of the GSS along the NSQM by 1.30 days, an advancement of the GSE by 0.89 days, and a shortening of the GSL by 2.20 days, and for the SSQM, the GSS was delayed by 1.88 days, the GSE advanced by 1.32 days, and the GSL was shortened by 3.20 days. Thus,

the changes in GSS, GSE, and GSL trends with latitude and topography varied greatly between the NSQM and SSQM. The SSQM exhibited a more significant trend than the NSQM, and regional differences in terrain regularity were prominently observed in the QMs. These trends are related to the unique terrain of the QMs, where the span in latitude from north to south is only 2.24°, but the elevation difference is very large. The QMs, which have the highest elevation in the eastern part of mainland China, create an extensive barrier effect that makes the northern and southern climates

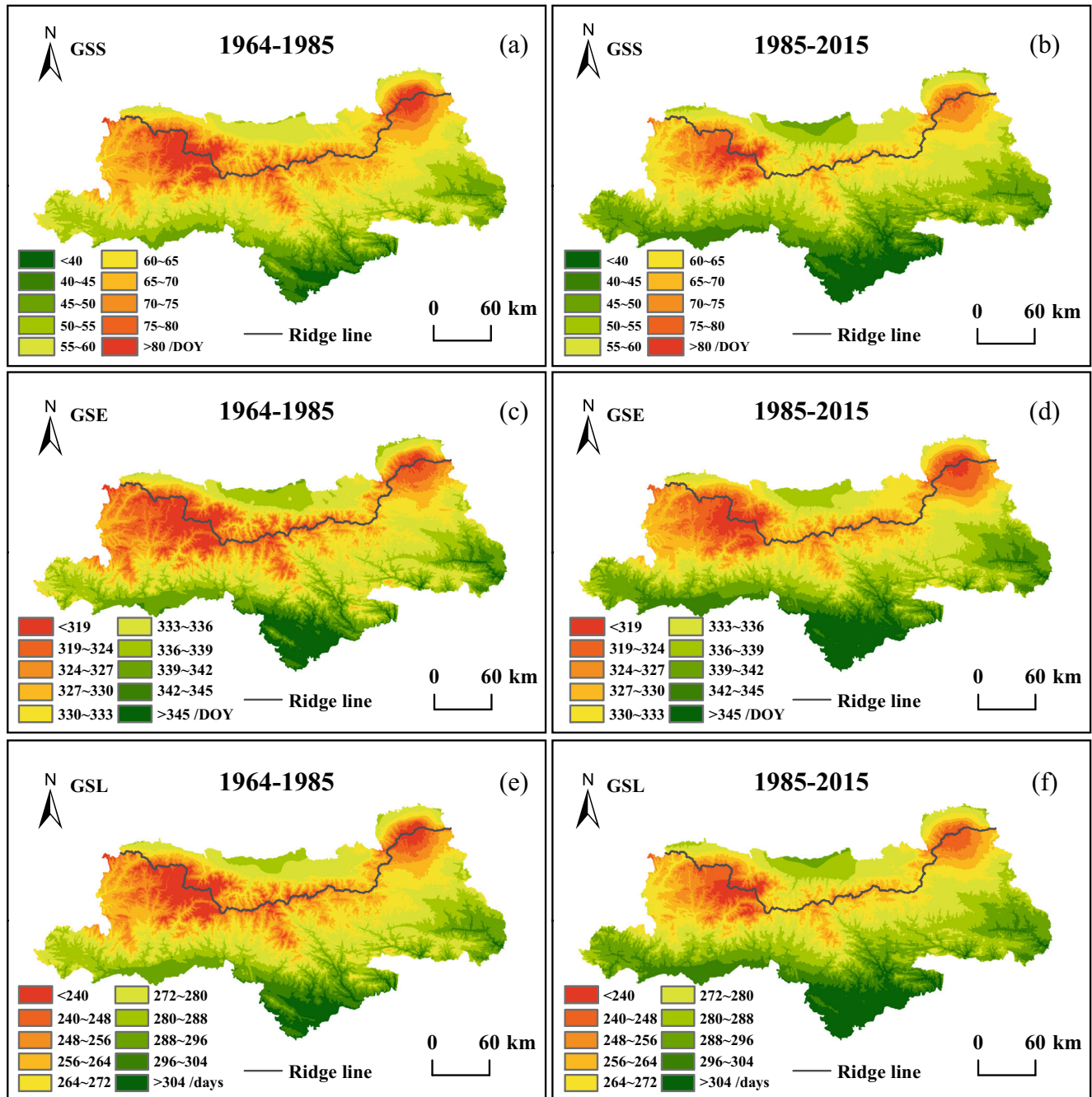


Fig. 5 Spatial distribution of the CGS parameters in the QMs before and after the abrupt change in temperature

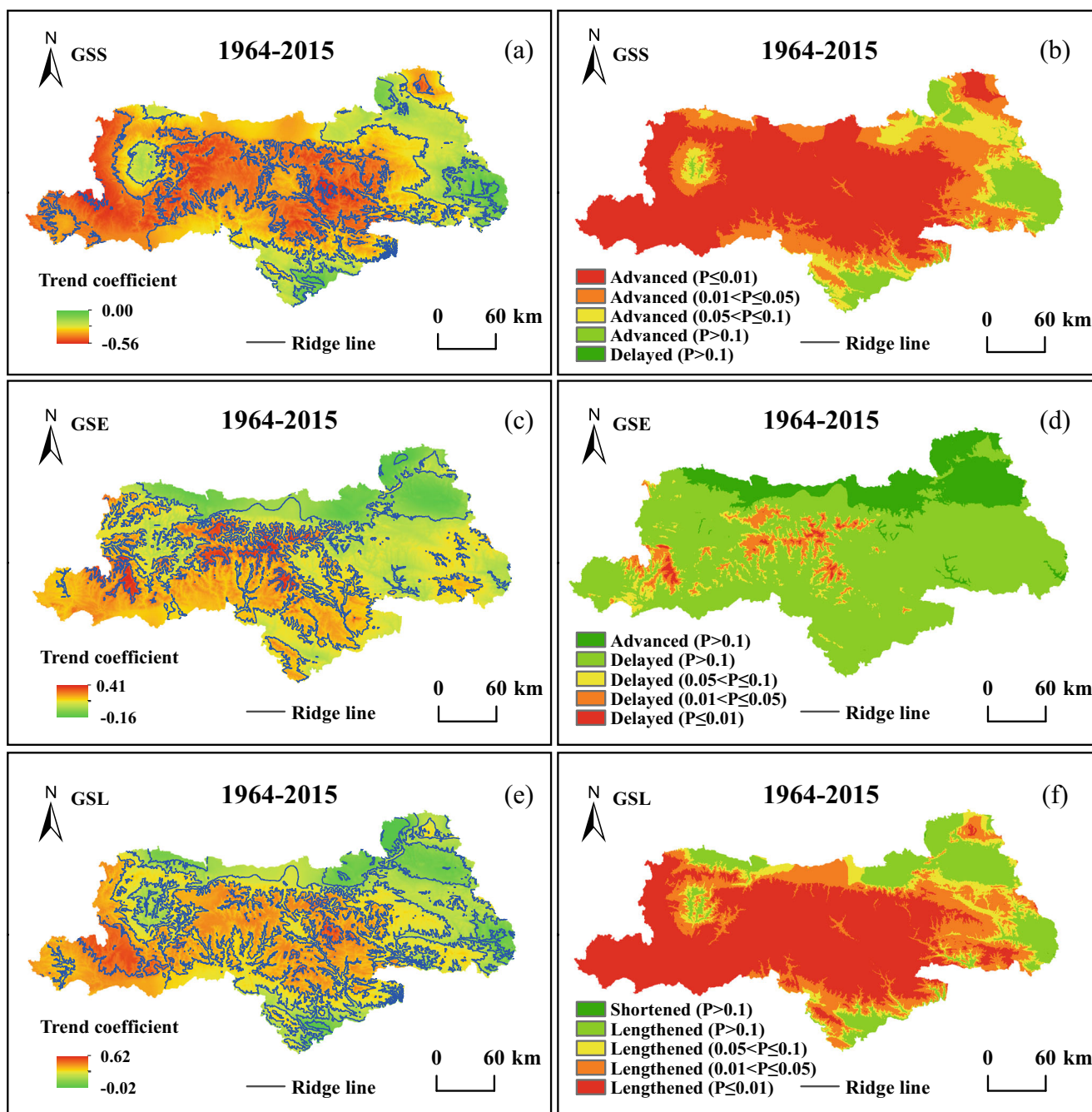


Fig. 6 Changes in the trend coefficients and significance in the CGS parameters in the QMs during 1964–2015

significantly differ. The climate of the NSQM is cold and dry, and the climate of the SSQM is warm and humid.

4.2.2 The CGS spatial distribution before and after the abrupt change in temperature

The spatial changes in the CGS parameters in the QMs were analyzed before and after the abrupt change in temperature (Fig. 5). Compared with those before the abrupt change, the GSS, GSE, and GSL after the abrupt change

showed advanced, delayed, and lengthened trends, respectively. Additionally, these trends extended to high-elevation areas in both the NSQM and SSQM. Before the abrupt change, an increase of 100 m in elevation resulted in a GSS delay of 1.42 days, GSE advancement of 1.11 days, and GSL shortening of 2.54 days in the NSQM area. For the same elevation change, the GSS was delayed by 2.0 days, the GSE advanced by 1.45 days, and the GSL was shortened by 3.46 days in the SSQM area. After the abrupt change, an increase of

100 m in elevation resulted in a GSS of 1.20 days, GSE advancement of 0.79 days, and GSL shortening of 1.99 days along the NSQM. Moreover, for the same change along the SSQM, the GSS was delayed by 1.81 days, the GSE advanced by 1.26 days, and the GSL was shortened by 3.07 days. Thus, the changes in the GSS, GSE, and GSL with elevation along the NSQM were larger than those along the SSQM after the abrupt change.

4.2.3 The spatial changing trends for the CGS during 1964–2015

The spatial changing trends for the CGS parameters in the QMs from 1964 to 2015 were also analyzed (Fig. 6). Over the past 52 years, the trend coefficients of the GSS in the QMs were almost all negative values; that is, the GSS displayed an advancing trend in the entire region. Based on the *t* test results, among the total area (100% of the study area) that displayed an

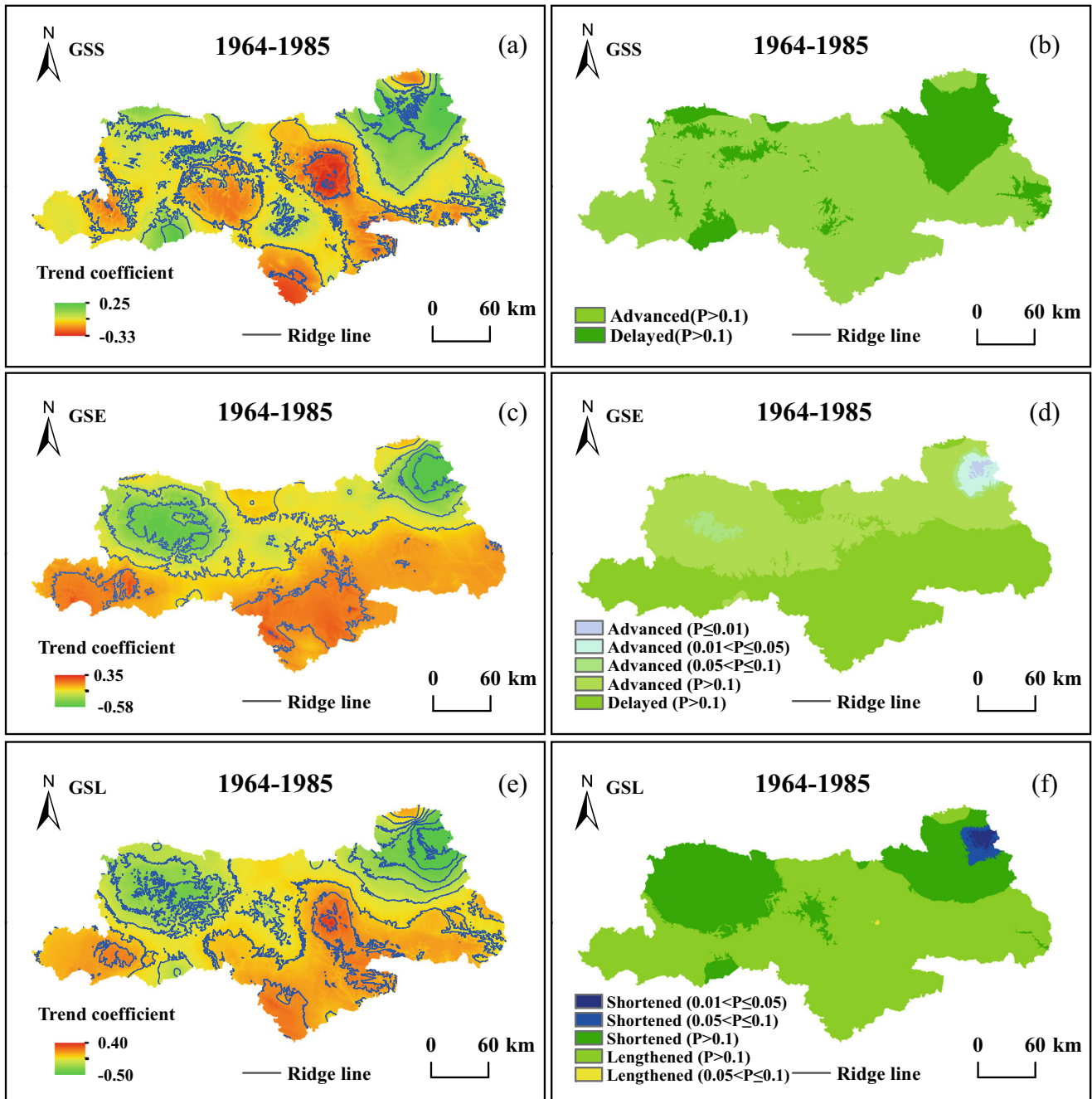


Fig. 7 Trend coefficients and significance of changes in the CGS parameters in the QMs during 1964–1985

advanced trend, 56.06%, 23.46%, 10.17%, and 10.31% of the trends exhibited high significance, significance, weak significance, and non-significance, respectively. The trend coefficients of the GSE were almost all positive values, except for those in low-elevation areas along the NSQM and the adjacent ridgeline on the eastern portion of SSQM; that is, the GSE showed a generally delayed trend in the entire region. Overall, 83.62% of the area exhibited a delayed trend, and the trends in 5.69%, 5.13%, and 72.80% of the area exhibited high significance and significance, weak significance, and non-

significance, respectively. Additionally, 16.38% of the area displayed a non-significant advancing trend. Almost all the trend coefficients of the GSL were positive values; that is, the regional GSL generally exhibited a lengthening trend. Among the lengthened areas, which accounted for 99.8% of the study area, 52.68%, 21.36%, 9.31%, and 16.63% of the results exhibited high significance, significance, weak significance, and non-significance, respectively. Thus, the GSS displayed a significant advancing trend, the GSE was delayed, and the GSL exhibited a significant lengthening trend in the QMs over the

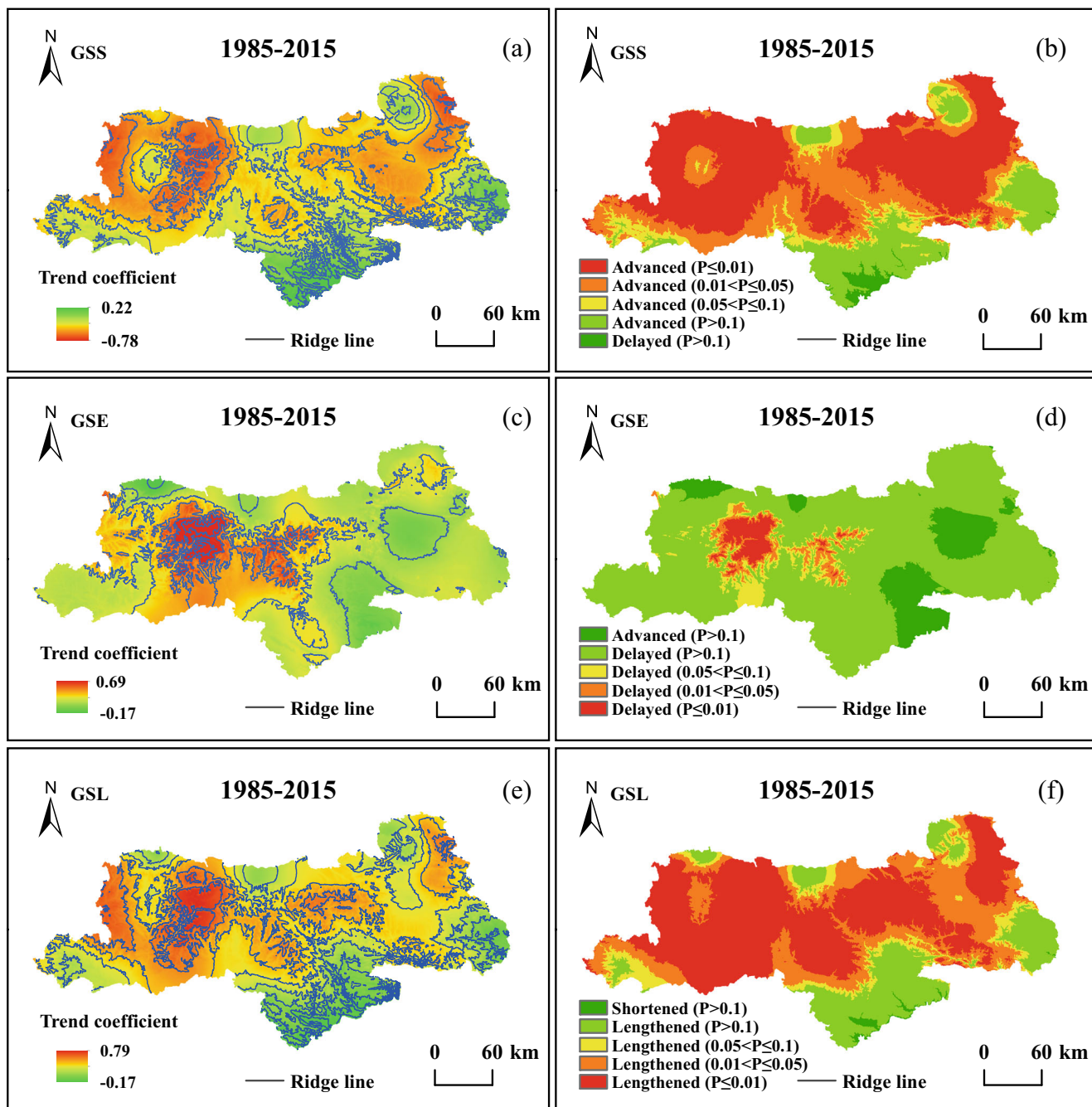


Fig. 8 Trend coefficients and significance of changes in the CGS parameters in the QMs during 1985–2015

past 52 years. The advancing trend in GSS was more significant than the delayed trend in GSE, and the extension of the GSL was mainly caused by the advanced GSS. These conclusions are consistent with previous research conclusions. Specifically, previous studies found that the spring phenophase along the northern hemisphere has advanced, the autumn phenophase has been delayed, and the GS has lengthened (Parmesan 2007; Gordo and Sanz 2009; Chen and Lin 2012). Additionally, the plant GS in Europe has lengthened due to the advanced spring phenophase (Chmielewski and Rölzer 2001). The spatially averaged rates of GSS, GSE, and GSL changes were 2.70, 0.66, and 3.36 days/decade, respectively. Based on the spatial distribution of the varying significance of trends, the advancing trend of the GSS and the lengthening trend of the GSL were most significant in high-elevation areas, and the GSE did not significantly change in most areas. For the NSQM and SSQM, the highly significant and significant results included the advancement of GSS along the NSQM (84.57%) and SSQM (78.23%), the delay of GSE along the NSQM (6.74%) and SSQM (5.44%), and the lengthening of GSL along the NSQM (55.84%) and SSQM (78.84%). In conclusion, the advancing trend of the GSS and the delayed trend of the GSE along the NSQM were more significant than those along the SSQM, but the lengthening trend of the GSL along the SSQM was more significant than that along the NSQM. The main reason for this difference was that the GSE along the NSQM displayed a non-significant advancing trend (50.86%), but that along the SSQM exhibited a non-significant delaying trend (81.81%); therefore, the differences in GSE changes had a decisive effect on the lengthening of the GSL.

4.2.4 The spatial changing trends for the CGS before the abrupt change in temperature

The spatial changing trends in the CGS parameters in the QMs during 1964–1985 were investigated (Fig. 7). Before the abrupt change in temperature, GSS in most areas of the QMs exhibited non-significant advancing (78.0%) and delaying (22.0%) trends, and the total areas with non-significant advancing trends reached 70.86% and 79.84% in the NSQM and SSQM regions, respectively. The GSE exhibited a non-significant advancing trend along the NSQM and in the northern part of the SSQM (41.33%) and a non-significant delaying trend in most other regions (54.28%). The GSE mainly exhibited a non-significant advancing trend along the NSQM (83.19%) and a non-significant delaying trend along the SSQM (64.70%). The GSL displayed non-significant shortening trends (31.34%) in the Mount Taibai area, Mount Hua area, and the surrounding areas, as well as non-significant lengthening trends in other areas (66.70%). Additionally, non-significant shortening and non-significant lengthening trends were observed along the NSQM (52.79%) and SSQM (72.04%), respectively. These findings indicate that the changes in the GSS, GSE, and GSL

were non-significant before the abrupt temperature change. The GSS mainly exhibited an advancing trend along the NSQM and SSQM, and the GSE and GSL displayed opposing trends in the NSQM and SSQM regions. Specifically, the GSE mainly advanced along the NSQM and was delayed along the SSQM, and the GSL was mainly shortened along the NSQM but lengthened along the SSQM.

4.2.5 The spatial changing trends for CGS after the abrupt change in temperature

The spatial changing trends in the CGS parameters in the QMs from 1985 to 2015 were analyzed (Fig. 8). After the abrupt change, the GSS was non-significantly delayed in low-elevation areas of the southernmost part of the SSQM, but it advanced in other regions. Of the 98.31% of the area with an advancing trend, 47.33%, 25.16%, 8.48%, and 17.33% of the results were highly significant, significant, weakly significant, and non-significant, respectively. Additionally, only 1.69% of the study area exhibited a non-significant delaying trend. Highly significant and significant advancing trends were observed in 82.80% of the area along the NSQM and 69.85% of the area along the SSQM. The delayed trend of the GSE was most significant in the Mount Taibai area and the region to the south of Mount Taibai. Overall, 87.26% of the area exhibited a delayed GSE trend, and 3.12%, 3.94%, 5.21%, and 74.99% of the results were highly significant, significant, weakly significant, and non-significant, respectively. Moreover, 12.74% of the total area displayed a non-significant advancing trend. The NSQM and SSQM mainly exhibited non-significant delayed GSE trends (78.93% and 73.95%, respectively). The GSL lengthening trend was significant in many areas, except in the low-elevation areas in the southern part of the SSQM region. In the 99.18% of the total area with a lengthening trend, 47.89%, 24.22%, 7.87%, and 19.2% of the results were highly significant, significant, weakly significant, and non-significant, respectively. The highly significant and significant delayed trends in the GSL reached 77.62% and 70.72% along the NSQM and SSQM, respectively. These results suggest that after the abrupt change, the GSS, GSE, and GSL trends were significantly higher than those before the abrupt change, and this shift may be closely related to a significant increase in the temperature in the QMs. In addition, the GSS, GSE, and GSL trends along the NSQM were significantly higher than those along the SSQM, possibly due to the difference in the amplitude of warming along the NSQM compared to that along the SSQM after the abrupt change.

4.3 Conclusions

Over the past 52 years, warming in the QMs displayed significant trends, and the temperature variations have exhibited spatial differences and characteristics related to the abrupt temperature change in 1984, with warming starting in the

mid-1980s. Before the abrupt change, the temperature changes in the QMs displayed a non-significant downward trend. However, after the abrupt change, the temperature increases were significant in the entire area, and the warming trend along the NSQM was significantly higher than that along the SSQM. The CGS in the QMs exhibited regular changes with temperature variations. The spatial distributions of the GSS, GSE, and GSL in the QMs varied based on regional differences in latitude and topography, and the regional ranges of the GSS, GSE, and GSL were generally largest in high-elevation areas. The GSS, GSE, and GSL were gradually delayed, advanced, and shortened, respectively, as latitude and elevation increased. Overall, the GSS in the QMs advanced, the GSE was delayed, and the GSL was lengthened. Before the abrupt change, the GSS, GSE, and GSL in the QMs were relatively stable, and their changes in amplitude were non-significant. The GSS and GSE exhibited non-significant advancing trends, and the GSL displayed a non-significant shortening trend. However, after the abrupt change, the GSS, GSE, and GSL changes were more significant than those before the abrupt change. The GSS exhibited a significant advancing trend, the GSE was delayed, and the GSL displayed a significant extension. The significant advance in the GSS was the main reason for the prolongation of the GSL. There were significant differences in the GSS, GSE, and GSL between the NSQM and SSQM. Before the abrupt change, the trend in the GSS was the same along the NSQM and SSQM, with both areas exhibiting an advancing trend. The trends in the GSE and GSL along the NSQM and SSQM were opposing. The GSE along the NSQM mainly exhibited an advancing trend, the GSE along the SSQM was mainly delayed, and the GSL was mainly shortened along the NSQM but extended along the SSQM. After the abrupt change, the GSS, GSE, and GSL trends along the NSQM were significantly greater than those along the SSQM. The GSS and GSL showed significant advancing and lengthening trends, respectively, along both the NSQM and SSQM, and the GSE displayed a delayed trend.

4.4 Discussion

Starting with the start and end times based on the threshold temperature, this study analyzed the CGS trends in the QMs from 1964 to 2015 in the context of climate warming. The results showed that the GSL lengthened by approximately 17.4 days on average over the past 52 years and the GSLs along the NSQM and SSQM lengthened by 16.6 and 18.1 days on average, respectively. After the abrupt change in temperature, the extension of the GSL in the QMs was particularly significant. Notably, the GSL of the entire area lengthened by 21.3 days, and the GSL extended by 24.6 and 20.7 days along the NSQM and SSQM, respectively. The GLS lengthening results of this study were relatively large compared with those of other scholars. For example, Liu

et al. (2010) showed that the GSL in China increased by 6.9–8.7 days from 1955 to 2000, and Xu and Ren (2004) found the GSL in China increased by 6.6 days from 1961 to 2000. Additionally, Song et al. (2010) found the GSL lengthened by 10.3 days from 1951 to 2007, including by 13.1 and 7.41 days in North and South China, respectively. This difference may be related to the unique climate of the QMs. The QMs have a massive barrier effect on the warm and humid airflow from the south in summer transported by the East Asian monsoon and the dry and cold airflow from the north in winter. This barrier effect causes the climate to significantly differ between the NSQM and SSQM. In the context of global warming, the increase in temperature along the NSQM is significantly higher than that along the SSQM. The unique geographical location of the QMs makes the area particularly sensitive to climate change, and its response to global climate change is more typical and representative. Therefore, it is of great significance to study climate change in the QMs.

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