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Spatiotemporal change in China's climatic growing season: 1955–2000

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Abstract The timing, length, and thermal intensity of the climatic growing season in China show statistically significant changes over the period of 1955 to 2000. Nationally, the average start of the growing season has shifted 4.6–5.5 days earlier while the average end has moved 1.8–3.7 days later, increasing the length of the growing season by 6.9–8.7 days depending on the base temperature chosen. The thermal intensity of the growing season has increased by 74.9–196.8 growing degree-days, depending on the base temperature selected. The spatial characteristics of the change in the timing and length of the growing season differ from the geographical pattern of change in temperatures over this period; but the spatial characteristics of change in growing degree-days does resemble the pattern for temperatures, with higher rates in northern regions. Nationally, two distinct regimes are evident over time: an initial period where growing season indicators fluctuate near a base period average, and a second period of rapidly increasing growing season length and thermal intensity. Growing degree-days are highly correlated with March-to-November mean air temperatures in all climatic regions of China; the length of the growing season is likewise highly correlated with March-to-November mean air temperatures except

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in east, southeast and southwest China at base temperature of 0°C and southeast China at base temperature of 5°C. The growing season start date appears to have the greater influence on the length of the growing season. In China, warmer growing seasons are also likely to be longer growing seasons.

1 Introduction

Climatic change has become an important issue for agriculture and forestry in recent decades. Global surface temperature has increased ≈0.2°C per decade over the past 30 years (Hansen et al. 2006), making the late twentieth century the warmest period in the past 1,800 years in the northern hemisphere and, likely, globally as well (Jones and Mann 2004). Human-induced greenhouse effect is most likely the main causation of the observed global warming during the late twentieth century (Jones and Mann 2004; IPCC 2007). The influence of climate change on the growing season of terrestrial vegetation can be analyzed through phenological observations, climatic measurements, and remote sensing based indicators.

Plant phenophases (such as bud-burst, bloom, leaf unfolding, leaf coloration, and defoliation) provide objective measures of the seasonal growth and senescence of terrestrial vegetation. The occurrence dates of plant phenophases from individual species have often been used to determine the beginning and end dates of the growing season. Several kinds of environmental change, including warming, elevated CO_2, nitrogen (N) deposition, and changes in precipitation, can affect the physiological processes of plants resulting in changes in phenology. Warming tends to accelerate both flowering and greening, but phenological responses to other kinds of environmental change are diverse (Cleland et al. 2006).

An increasing number of studies report changes in plant phenology as well as animal behavior, differing from species to species across many regions of the world (Peñuelas and Filella 2001). An analysis of over 30 years of observations in Europe found that spring events, such as leaf unfolding, have advanced by 6 days, whereas autumn events, such as leaf coloring, have been delayed by 4.8 days. These shifts in the growing season were attributed to changes in air temperature (Menzel and Fabian 1999). In Britain, Fitter and Fitter (2002) found the average first flowering date of 385 plant species has advanced by 4.5 days during the past decade compared with the previous four decades, with large differences among species. Schwartz and Chen (2002), analyzing Chinese data for 1959–1993, found that the earlier last spring frost dates did not correspond with earlier spring vegetative growth, and pointed instead to changes in the diurnal temperature range and day-to-day temperature differences. Zheng et al. (2002) noted a nonlinear relationship between temperature change and spring phenophase change in China over 40 years. However, at five stations in China, Tao et al. (2006) found that changes in temperature have shifted crop phenology and affected crop yields over the course of two decades, with regional differences. In Korea, five species of trees and shrubs experienced increasingly early first bloom dates from 1922 to 2004; increased heat accumulation related to warming trends was implicated as a major factor for these observed changes (Ho et al. 2006). But as pointed out above, changes in plant phenology cannot necessarily be attributed to increase of temperature alone, as it is difficult to separate the effect of temperature change from other influences.

As phenological data are comparatively scarce in many parts of the world, the growing season can be measured at larger scale using satellite data. The Normalized Difference Vegetation Index (NDVI) is a commonly used indicator of vegetation dynamics derived from visible and near-infrared satellite imagery. An analysis by Tucker et al. (2001) strongly supports a variety of different reports in the literature of an earlier start and later end to the growing season at higher northern latitudes directly linked to increasing surface temperatures. Likewise, Fang et al. (2004) analyzed variations in NDVI during the past 18 years in China and found that vegetation activity has been rising in recent years, with extended growing seasons and increased plant growth rates accounting for the change. However, NDVI metrics and thresholds may not directly correspond to conventional, ground-based phonological events. Chen and Pan (2002), analyzing the relationship between phenological, meteorological, and NDVI data, suggested that annual mean air temperature, annual number of growing degree days, mean air temperature during late winter and spring, and growing season time-integrated NDVI are the most important controls on length of the growing season.

Several strands of research have analyzed the influence of climate change on the growing season of terrestrial vegetation using meteorological data. Temperature is a key environmental factor for vegetation growth, and several temperature-derived variables can be used as indirect indicators of the plants' growing conditions. Each organism has a base temperature below which plant development does not occur; its climatic growing season is defined as the period when daily temperatures consistently rise above that level (Kadioğlu and Şaylan 2001). The start, end, and length of the climatic growing season (GSS, GSE, and GSL, respectively) are important environmental parameters. Likewise, the annual total growing degree days—GDD, calculated as the accumulation of daily mean temperatures above a given base level during the growing season—is an important agroclimatological energy term. Because the base temperatures and other restrictions used in calculating these parameters differ among studies, we will specify these conditions in parentheses after these terms, e.g., GSL (>5°C) refers to the length of the season with mean daily temperatures greater than 5°C.

Agriculture and forestry are highly dependent on climate. During the past century, changes in temperature patterns had a direct impact on the number of frost days and the length of growing seasons with significant implications for agriculture and forestry (Salinger 2005). Based on a global dataset, a significant lengthening of the thermal growing season (>5°C) can be observed in the extra-tropics of the Northern Hemisphere during the second half of the twentieth century (Frich et al. 2002). While a 200-station study of the former Soviet Union found little change in growing season (>5°C) related variables over the past 110 years (Jones and Briffa 1995), a large number of studies have confirmed the global trend with local variations. For example, in Canada, Bonsal et al. (2001) found that GDD (>5.5°C) have significantly increased over most of the country over the twentieth century. For the Canadian province of Alberta, Shen et al. (2005) found no significant long-term changes in GSS, GSE, or GSL (>5°C), but Bootsma (1994), examining the long term trends of selected agroclimatic parameters at five locations across Canada, documented a later

GSE and increased GDD (>5°C) for western Canada and lack of change in eastern Canada, consistent with the change of average temperatures for the same period.

Carter (1998) analyzed the start, end, duration, and intensity of the thermal growing season (>5°C) from 1890 to 1995 in the Nordic region, and found that the growing season lengthened considerably at all sites between 1891–1925 and 1926–1960, though the increase in recent years was at a slower rate at Fennoscandian sites and was not observed in Iceland. Feng and Hu (2004) analyzed the agrometeorological environment and found that GSL (>5°C) exhibited an increasing trend in the north and west of the USA, but a decline in the south and southeast USA. A study on daily minimum air temperature from the central US state of Illinois suggests that the GSL (>0°C) became roughly one week longer during the twentieth century (Roberson 2002). In Turkey, statistically significant decreasing trends of GDD (>5°C) in summer and autumn in coastal areas are reported by Kadioğlu and Şaylan (2001). Moonen et al. (2002) found an increasing trend in GSL (>0°C) in Italy. And Menzel et al. (2003) observed that the lengthening of the phenological growth period of trees in Germany, from leaf unfolding to leaf coloration, is mirrored by an increase in GSL (>5°C). GSL and GDD can also be used as indicators for discerning natural regional boundaries. Sha et al.'s (2002) analysis of the changes of natural regional boundaries in China used growing season length and growing degree days (>10°C) and detected a general northward shift of climatologically defined regions between 1951–1980 and 1981–1999.

China, though one of the most highly endowed countries in terms of territory and natural resources, nonetheless has a per capita cultivated area only one-third of the world's average (Chen et al. 1993). Food security has long been a central concern of the Chinese authorities, and the sustainable development of natural resources is now receiving unprecedented attention in China (Henderson 2004). An understanding of the influence of climate change on agriculture and forestry is of capital importance to these issues. Recent studies have documented a warming trend in China over the later half of the twentieth century, with regional differences (Qian and Xiang 2004; Liu et al. 2004), and 1998 is labeled as the warmest year since 1880 (Wang and Gong 2000). GSL (>5°C) increased significantly at most North and Northeast China stations during 1961–2000 (Qian and Xiang 2004). Liu et al. (2006) finds an increase in growing season length (>0°C) of approximately 17 days over the eastern and central Tibetan Plateau during 1961–2003.

In addition to the regional differences in the magnitude of temperature change, the seasonal timing of change also differs regionally, with northern Chinese sites seeing warmer temperatures earlier than those in southern China (Qian and Zhu 2001). Thus research needs to address the temporal character of national and regional climate change trends. The aim of this study is to examine the effects of regional climate change on the biometeorological environment with GSS, GSE, GSL, and GDD as key indicators of growing season (see Table 1).

Table 1 Acronyms and unit of temperature derived variables in this study

Acronym	Meaning	Unit
GSS	Start of growing season	Julian day
GSE	End of growing season	Julian day
GSL	Length of growing season	Day
GDD	Growing degree-day	Degree-day

2 Data and data analysis

2.1 Data sources

Data for this study consist of daily temperature records provided by the China Meteorological Administration through a bilateral agreement with the US Department of Energy for joint research on global and regional climate change (Riches et al. 2000). The dataset includes daily mean temperature records from 306 stations for the period of 1951–2000. The climate stations were well distributed across China including the Tibetan Plateau. Temperature were measured four times daily (at 0200, 0800, 1400, and 2000 hours), and the daily mean temperature was obtained by averaging the four measurements.

We applied several measures to assure data quality. According to Li et al. (2004a, b), abrupt changes in the time series of a single station are most likely caused by the relocation of the station. For each station, the time series was tested visually in different plots to exclude larger breaks in homogeneity. As a result of this inspection, we excluded one station near Shanghai after detecting an abrupt change in the time series around 1960.We have excluded records from prior to 1955 due to inconsistent or missing measurements for some stations; records after that date have been assessed to assure consistency and quality (Liu et al. 2004)

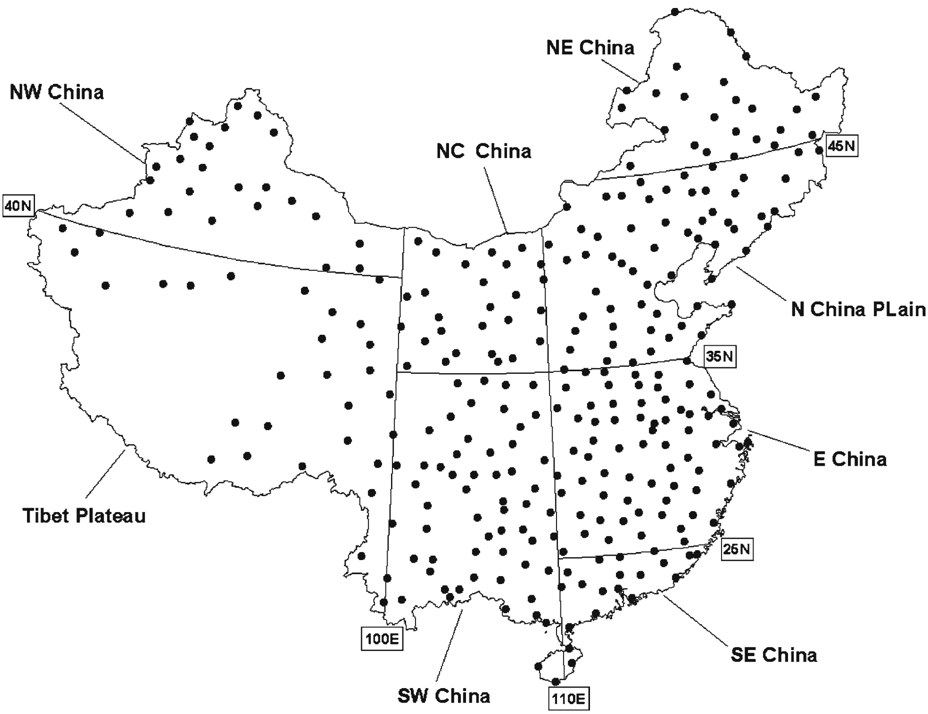


Fig. 1 The eight climatic regions of China and the spatial distribution of the 305 weather stations used in this study

Missing data are inevitable for long-term monitoring at most stations. Missing data accounted for less than 0.38% of the total records from 1955 to 2000 for daily temperature. Where data were missing for up to seven consecutive days, we used a simple linear interpolation algorithm to fill the data gaps. We used a stepwise regression to fill the gaps when the data were missing for more than seven consecutive days. The stepwise regression was performed every 5 years, with the missing station as the dependent variable and all of the other stations that had no missing values for the variable, considered after the simple linear interpolation, as independent variables. The stepwise regression gave a minimum coefficient of determination R^2 of 0.992, and most data gaps were only 1–2 days. We used the gap-filled dataset in this study considering the fact that the missing data were not randomly distributed along the time series but rather had more data missing in the early years.

Table 2 Regional averages of the four temperature-derived variables

	GSS	GSE	GSL	GDD
Tmean above 0°C				
Northeast China (NE)	98	294	197	2764
North China Plain (NCP)	75	318	244	3814
East China (E)	21	360	341	5935
Southeast China (SE)	1	365	365	7843
North Central China (NC)	78	311	234	3306
Southwest China (SW)	14	359	346	5810
Northwest China (NW)	79	309	231	3656
Tibetan Plateau (TP)	72	315	244	3049
Tmean above 5°C				
Northeast China (NE)	115	278	164	1817
North China Plain (NCP)	95	300	207	2634
East China (E)	56	343	288	4224
Southeast China (SE)	8	364	358	5986
North Central China (NC)	100	291	192	2179
Southwest China (SW)	39	348	309	4074
Northwest China (NW)	97	291	195	2530
Tibetan Plateau (TP)	101	291	191	1903
Tmean above 10°C				
Northeast China (NE)	135	261	128	1030
North China Plain (NCP)	114	282	169	1641
East China (E)	85	321	238	2817
Southeast China (SE)	39	357	319	4124
North Central China (NC)	125	270	146	1262
Southwest China (SW)	75	322	248	2556
Northwest China (NW)	118	273	156	1579
Tibetan Plateau (TP)	132	265	134	1032
Tmean above 15°C				
Northeast China (NE)	159	242	84	432
North China Plain (NCP)	138	262	125	844
East China (E)	111	297	187	1666
Southeast China (SE)	76	335	260	2514
North Central China (NC)	149	248	100	579
Southwest China (SW)	110	289	180	1362
Northwest China (NW)	142	254	113	822
Tibetan Plateau (TP)	158	238	81	483

We recognize that it is difficult to eliminate the influence of urban growth (specifically the urban heat island effect) on daily temperature measures. China has seen a rapid expansion of urban areas, especially in the post-Mao reform period beginning in 1978. Controversy has persisted over the influence of urban warming on reported surface-air temperature trends in China. Zhou et al. (2004) presents evidence for a significant urbanization effect on climate based on analysis of impacts of land-use changes on surface temperature in southeast China for over several recent decades. Similar result can be find in research work on urbanization effect on air temperature in north China (Ren et al. 2008). On the contrary, Li et al. (2004a, b), and Jones et al. (2008) finds little effect of urbanization on the observed warming in China over the past several decades, similar to the results for other periods and locations. In a preliminary study we removed 45 urban weather stations, located in cities with a population larger than one million, from the 305 stations to evaluate the urbanization effect on China's climate change in the past decades. As might be expected, temperatures in the urban stations increased slightly faster than those in the nonurban stations. However, similar to the findings of Li et al. (2004a, b), and Jones et al. (2008), the temporal change of the two time series (with urban stations and without urban stations) was not significantly different. Further research is needed on role of urbanization on temperature trends in China.

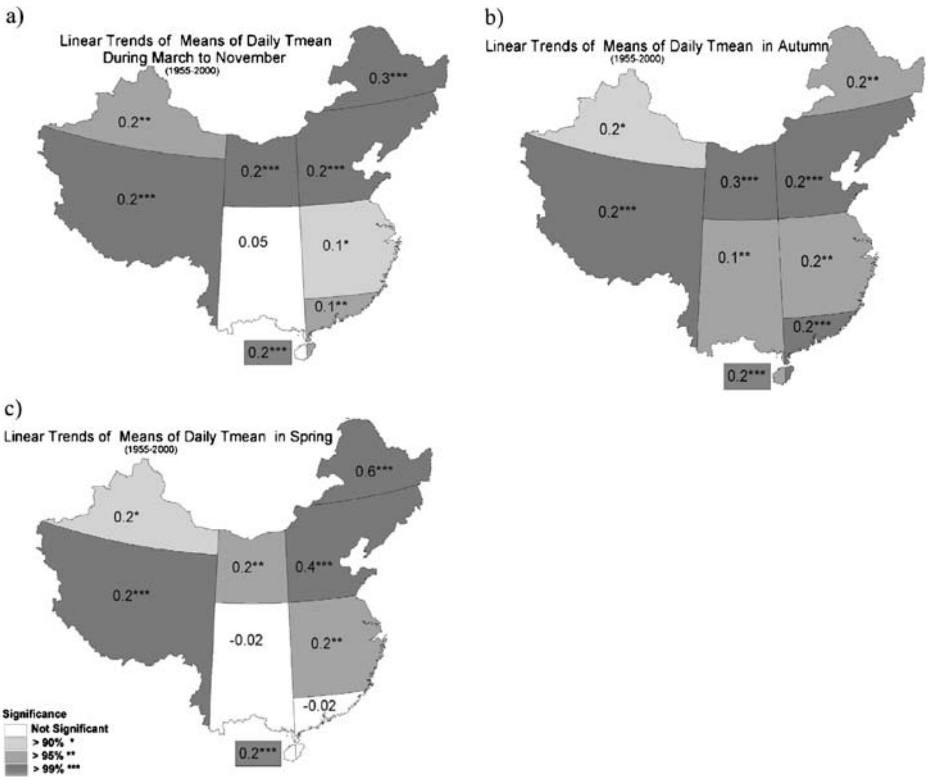


Fig. 2 Significance and magnitude of trends of daily mean temperature (°C) during **a** March to November; **b** Autumn and **c** Spring; *box* at lower center gives the national trend

In our analysis, we use daily mean temperature records from 305 stations for the period of 1955 to 2000. Figure 1 shows the distribution of the stations used in this analysis and the division of China into eight climatic regions, as defined by Liu et al. (2005).

2.2 Definitions of growing season parameters

Phenologically speaking, the annual growing season runs from the initiation of sap flow to the wilting of leaves. As noted above, each organism has a base temperature below which plant development does not occur; additionally, plants need a certain amount of heat for each growing phase and if a heat deficit occurs in one phase then the subsequent phase will not begin (Chen et al. 1993). The length of the growing season determines the annual vegetation productivity with longer seasons favoring the accumulation of organic matter.

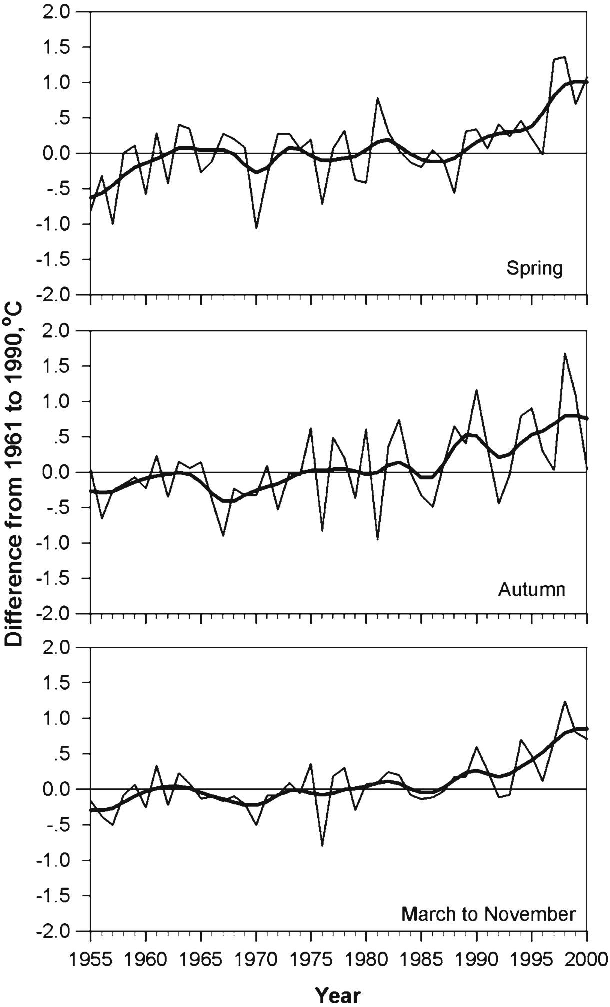
Base temperatures vary among species and can be determined empirically, but as a rule, agricultural activities in China are performed in the period when daily mean temperatures remain consistently above 0°C (Chen et al. 1993). The growing phase increases from north to south in China. In the temperate zone, seeds start spouting when air temperatures reach 5°C and commence growing in soil temperatures of 5°C. The period with daily mean temperatures above 5°C is generally regarded as the growing season for most cool-season crops and trees, with the most active growth period in temperatures above 10°C; the corresponding periods for warm-season crops are at temperatures 5°C hotter (Xin et al. 1999).

Recognizing the different possible definitions of the climatic growing season, in this study we adopt four temperature thresholds—0°C, 5°C, 10°C, and 15°C—and calculate the start and end dates of each thresholded growing season for each year at each climate station. Furthermore, recognizing that growing-season statistics based on a single-threshold air temperature can sometimes be misleading (Brinkmann 1979), we instead make use of integrative smoothing measures as recommended by Menzel et al. (2003). To accomplish this, we calculated the 5-day running mean temperatures beginning with the fourth day before daily mean temperatures first rise above the base temperature. We then identified the period that the 5-day running mean temperatures remain above the base temperature, noting X_b and X_e, the beginning and ending dates of this period. GSS was calculated as the first day between dates X_{b-2} and X_{b+2} that the daily mean temperature rises above the base temperature; GSE is the last day between dates X_{e-2} and X_{e+2} that the daily mean temperature remains above the base temperature. GSL, then, is the number of days from GSS to GSE, inclusive. GDD was calculated as the sum of the departures of the daily mean temperature from the base temperature from GSS to GSE.

2.3 Data analysis

We analyzed the spatial and temporal changes in the GSS, GSE, GSL, and GDD for the four base temperature thresholds of 0°C, 5°C, 10°C, and 15°C. First, for each station we calculated a time series of anomalies (from the 1961–1990 base period average) of the above derived temperature indices and the seasonal averaged temperatures for spring (March–May), autumn (September–November), and the entire spring-summer-autumn (SSA) period of March to November. We then created a time series for each climatic region based on the arithmetic average of all stations in each region; we also generated a national time series from an area-weighted average of the climatic region values. We calculated simple linear trends for each regional and national time series. We note that autocorrelation is not a problem in this study because the regression was performed on annual and regional basis; we confirmed this by using the Durbin–Watson statistic to test the time series for first-order autocorrelation. In order to analyze temporal variation, we applied a nine-point binomial filter to smooth out the year-to-year variations in a time series and show the longer-term trend. Finally, a correlation analysis was conducted to examine the relationships among the time series of the variables.

Fig. 3 Time series of national averaged daily mean temperature. The *heavy line* is the result of smoothing with a nine-point binomial filter with reflected ends



3 Results

The regional averaged temperature-derived variables are summarized in Table 2. As would be expected, it is immediately evident that GSS comes earlier and GSE arrives later in the southern regions than in the north of China, and that both GSL and GDD are greater in the south.

3.1 National and regional change character of Tmean

The national trend of average Tmean is similar for spring, autumn, and SSA (March–November) period, increasing significantly at the rate of 0.2°C per decade (see Fig. 2); the annual trend is increasing at the same rate. On a regional basis, the Tmean trend for the SSA period is similar to that for spring, with the greatest increases in north and northeast China. The trends for autumn are similar across most of the climatic regions except for north central and southwest China. All the climatic regions show increasing trends in all three periods, with exceptions only for southeast and southwest China in spring. These results on regional trends are similar to those reported in a separate analysis of 486 stations spanning 1960–2000 (Qian and Qin 2005).

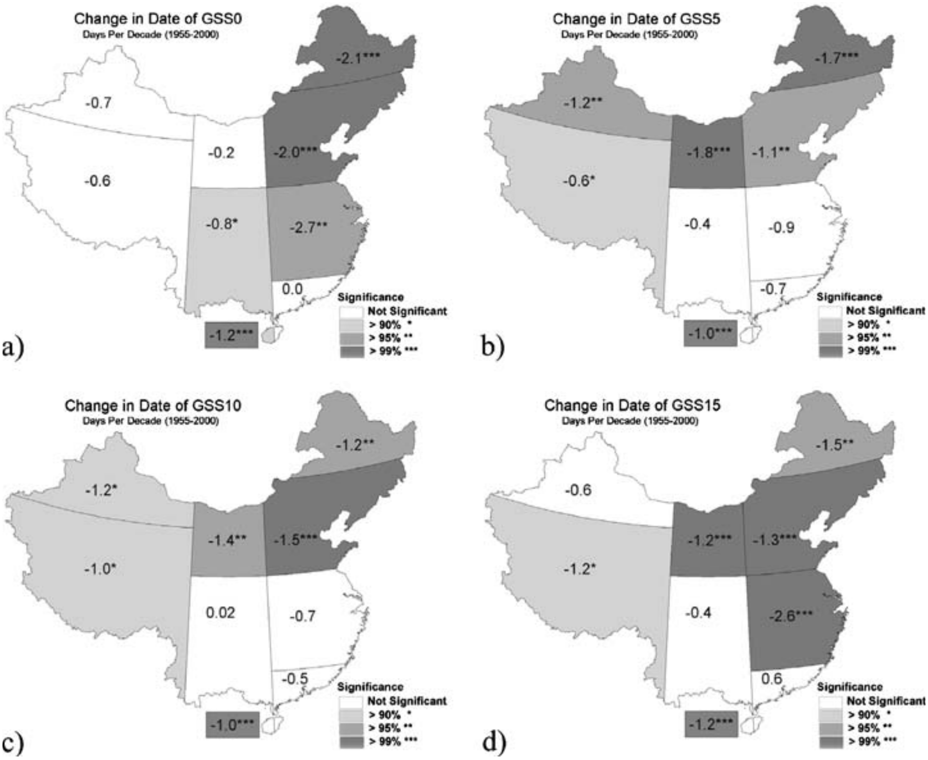


Fig. 4 Significance and magnitude of trends of the growing season start date (GSS) for base temperatures **a** 0°C; **b** 5°C; **c** 10°C; and **d**15°C. *Box* at lower center gives the national trend

Nationally, the temporal variation in Tmean is similar in spring, autumn, and the SSA period, with rapid increases observed around 1987 (Fig. 3), as reported by Liu et al. (2004) and Qian and Qin (2005). Regional temporal variation in Tmean (not shown) are similar to the national pattern.

3.2 Trends in the temperature derived variables

The regional and national trends of GSS (in days per decade) for the base temperatures of 0°C, 5°C, 10°C, and 15°C are shown in Fig. 4. We find that the national average start of the growing season has become earlier by 4.6 to 5.5 days, depending on the base temperature, over the 46-year study period. The change in GSS is significant for all four base temperatures, and the rates of change rate for all the four are similar. Region by region and for all four base temperatures, the trends are in the same direction with only two exceptions, though levels of statistical significance vary. Only the northeast and North China Plain present significant trends of earlier GSS for all four base temperatures. In two cases—southwest China for GSS (>10°C) and southeast China for GSS (>15°C)—trends toward later GSS are observed, though they are below the threshold of statistical significance. These may related to the

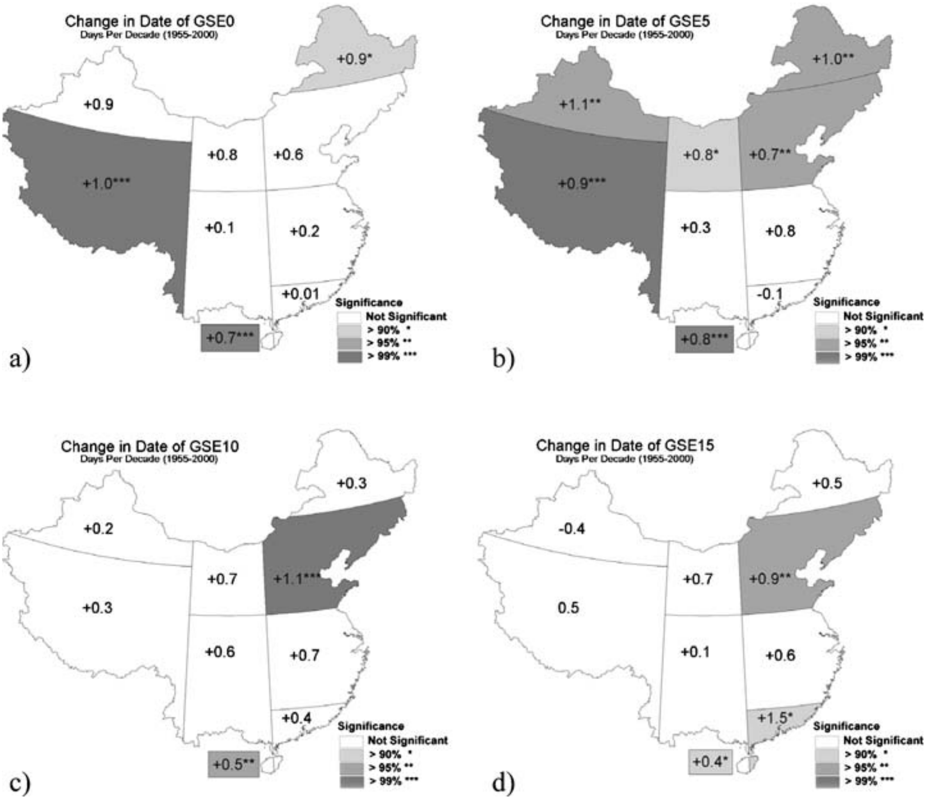


Fig. 5 Significance and magnitude of trends of the growing season end date (GSE) for base temperatures **a** 0°C; **b** 5°C; **c** 10°C; and **d**15°C. *Box* at lower center gives the national trend

slightly decreasing trend of averaged spring Tmean for these two climatic regions (see Fig. 2c). We note that the higher base temperatures do not see lower rates of change, and that the spatial patterning of GSS trends are unlike that of spring Tmean, where the higher rates of increase are consistently in the northern regions.

The regional and national trends of GSE for the base temperatures of 0°C, 5°C, 10°C, and 15°C are shown in Fig. 5. We find that, on average nationally, the end of the growing season moved later by 1.8 to 3.7 days, depending on the base temperature. This magnitude of change is less than that of GSS, and though it is significant for all four base temperatures, their rates vary. On a regional basis, magnitudes and levels of significance vary, and again there are two exceptions to the general movement: southeast China for GSE (>5°C) and northwest China (>15°C) show nonsignificant trends toward earlier GSE dates. As with the GSS trends, higher base temperatures do not see lower rates of change, and the spatial pattern of these trends of GSE is not like that of autumn Tmean.

Turning to the length of the growing season, the regional and national trends of GSL for the four base temperatures are shown in Fig. 6. We find that the national average length of the climatic growing season has increased by 6.9 to 8.7 days and that the trend is statistically significant for all four base temperatures. Regionally, as with

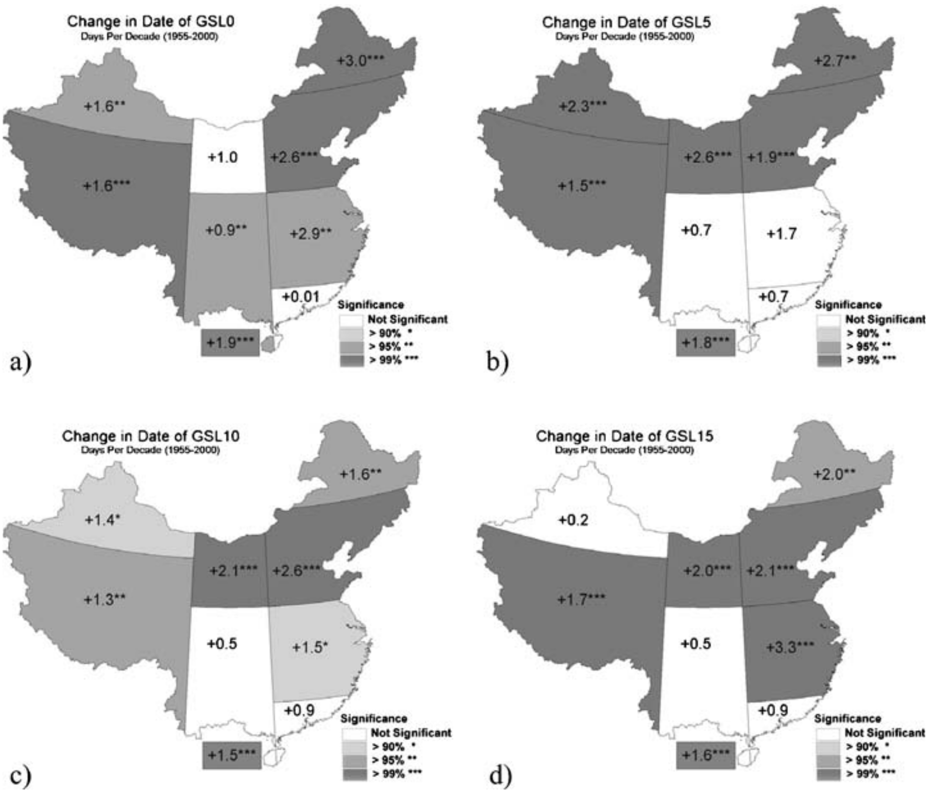


Fig. 6 Significance and magnitude of trends of the growing season length (GSL) for base temperatures **a** 0°C; **b** 5°C; **c** 10°C; and **d** 15°C. *Box* at lower center gives the national trend

GSS and GSE, the change in GSL differs among the base temperature, but there are no regional exceptions to the increasing trend. Again, the higher base temperatures do not see lower rates of change, and the spatial patterning does not follow that of the spring-summer-autumn Tmean.

The regional and national trends of annual GDD for base temperatures of 0°C, 5°C, 10°C, and 15°C are shown in Fig. 7. We find that the national averaged GDD has increased by 74.9 to 196.8 degree-days. The change is significant for all four base temperatures, both nationally and in all climatic regions. Lower base temperatures are associated with higher rates of change in GDD nationally and for all but one climatic region; in southeast China, the trend for GDD (>0°C) is slightly less than that for GDD (>5°C). The spatial patterning trends of GDD does resemble that for Tmean in the SSA period with climate region of southeast China being an exception.

3.3 Temporal variations in the temperature derived variables

In order to analyze changes in the timing and length of the growing season and growing degree-days, we calculated national and regional time series for different base temperatures. Again, a nine-point binomial filter with reflected ends was applied to highlight trends. Figure 8 shows the time series of national average GSS, GSE,

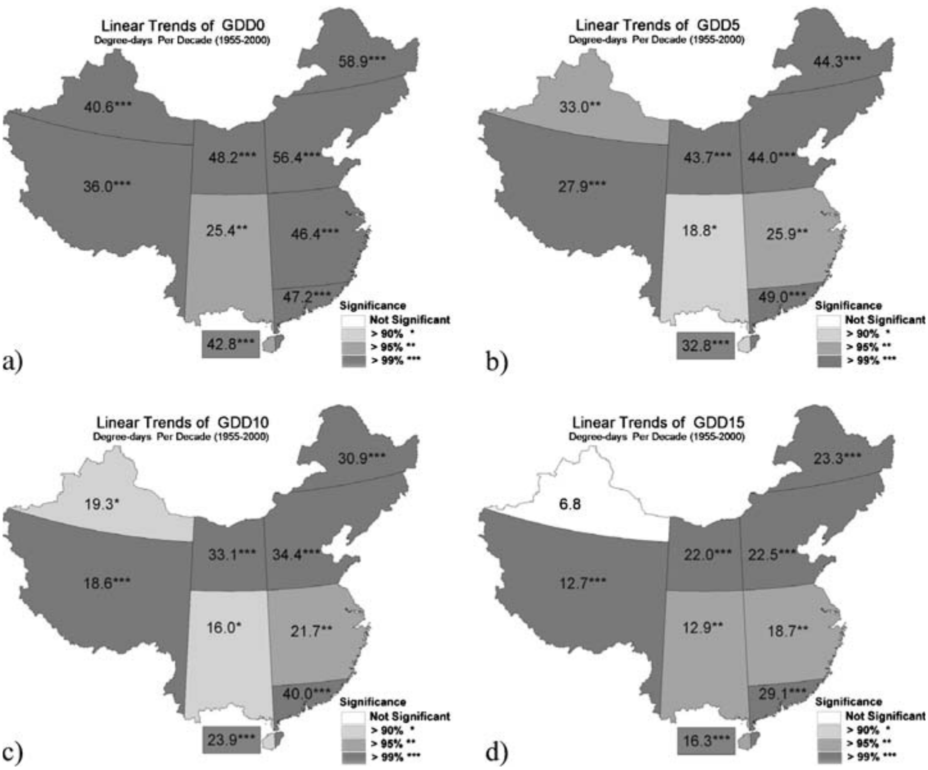


Fig. 7 Significance and magnitude of trends of growing degree-days (GDD) for base temperatures **a** 0°C; **b** 5°C; **c** 10°C; and **d** 15°C. *Box* at lower center gives the national trend

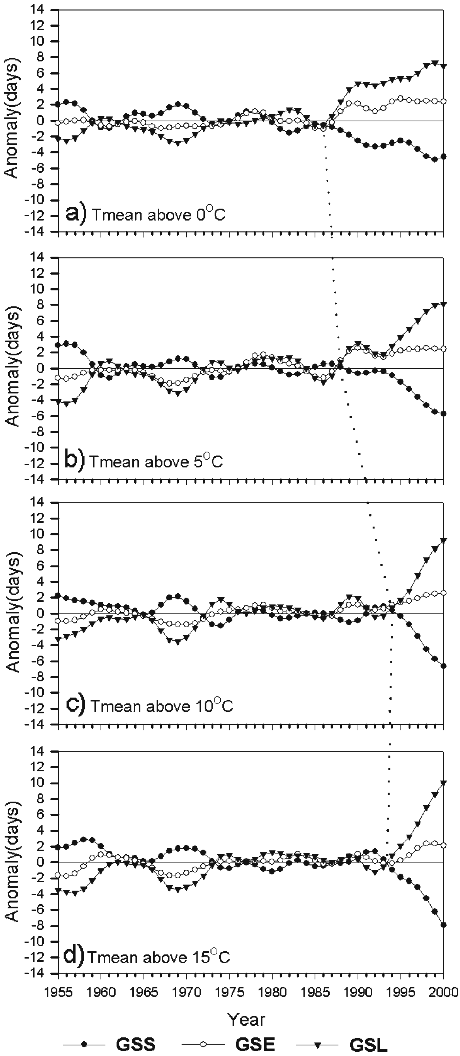


Fig. 8 Time series of national averaged GSS, GSE and GSL anomalies (from the 1961–1990 mean) for four base temperatures, indicating their respective turning points between temporal regimes. The values have been smoothed with a 9-year binomial filter with reflected ends

and GSL anomalies (departures from the 1961–1990 base period mean). Here we see two distinct regimes. During first period, GSS, GSE and GSL all fluctuate near the base period average. In the second period, the GSS arrives earlier and GSL later, producing a rapid lengthening of growing season. The turning point between the two regimes varies with the base temperatures, earlier for the lower base temperatures (1985 for base temperature 0°C and 1987 for 5°C) and later for the higher base temperatures (1992 for 10°C and 1993 for 15°C).

Figures 9, 10, 11 and 12 show the time series of regional average GSS, GSE, and GSL anomalies for the four base temperatures. For most climatic regions and base temperatures, we can also discern two distinct regimes, although in some cases the distinction is not so obvious as for the national average. As with the national trends, though, the turning point between the first regime of fluctuating GSL to the second

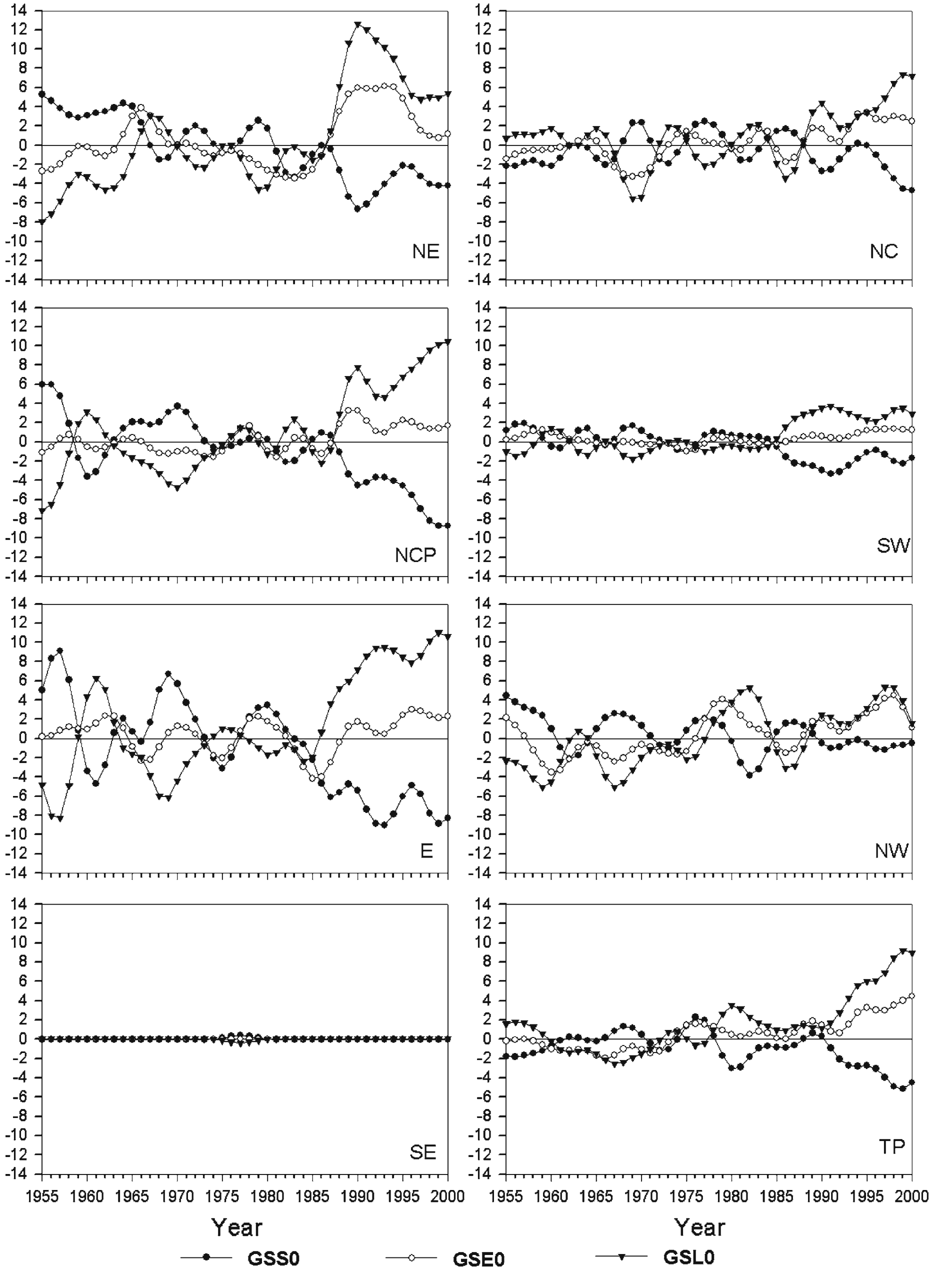


Fig. 9 Time series of regional averaged GSS, GSE, and GSL (>0°C) anomalies (from the 1961–1990 mean). The values have been smoothed with a 9-year binomial filter with reflected ends

regime of rapidly increasing GSL comes earlier for lower base temperatures. For example, in Northeast China the turning points for the 0°C, 5°C, 10°C, and 15°C base temperatures are 1986, 1988, 1993, and 1993 respectively.

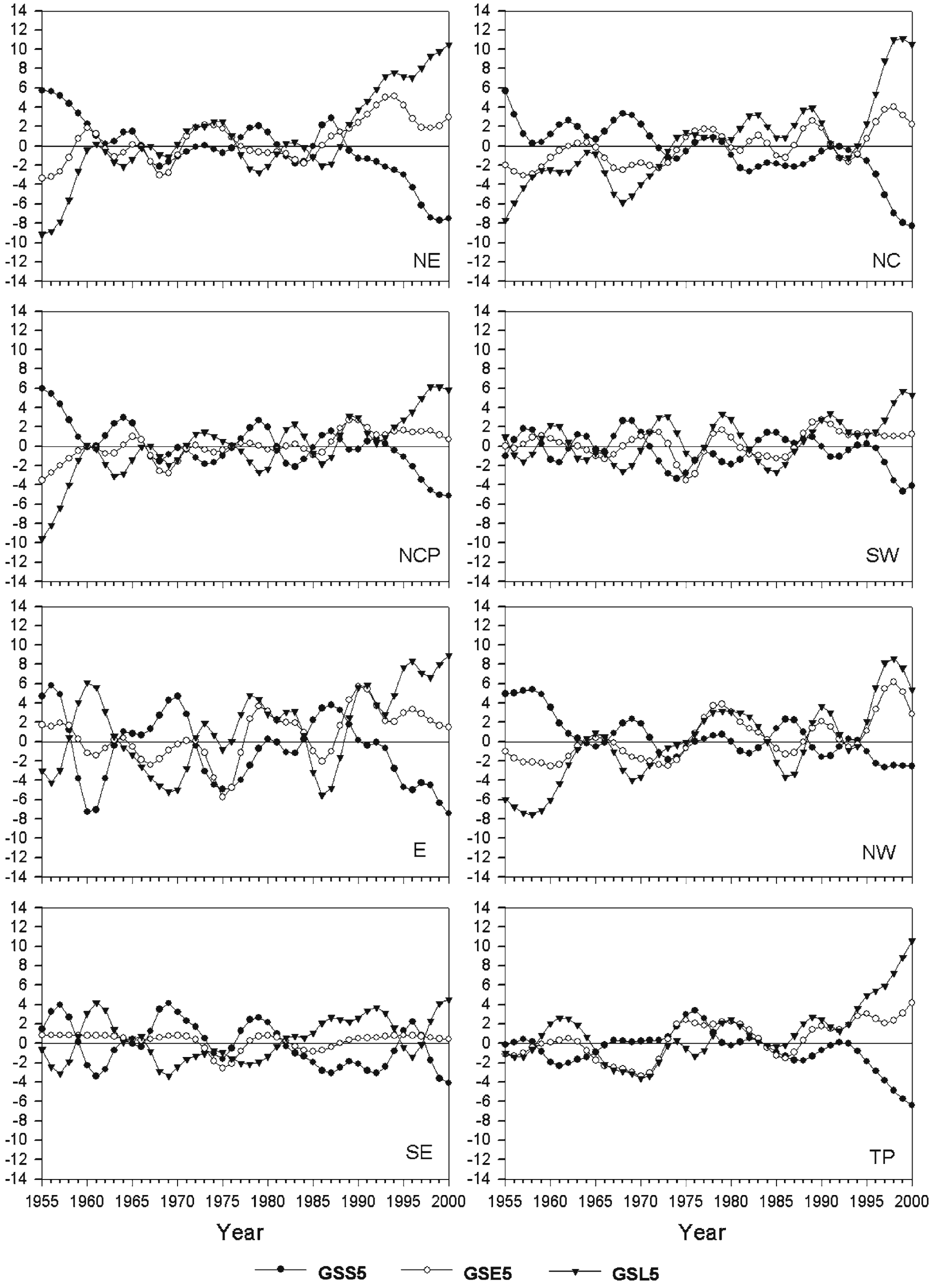


Fig. 10 Time series of regional averaged GSS, GSE, and GSL (>5°C) anomalies (from the 1961–1990 mean). The values have been smoothed with a 9-year binomial filter with reflected ends

Departures from the first regime may be noted in some climatic regions. The most obvious is in Southeast China for base temperatures 0°C and 5°C, which see almost no fluctuation around the base period average. The explanation for these

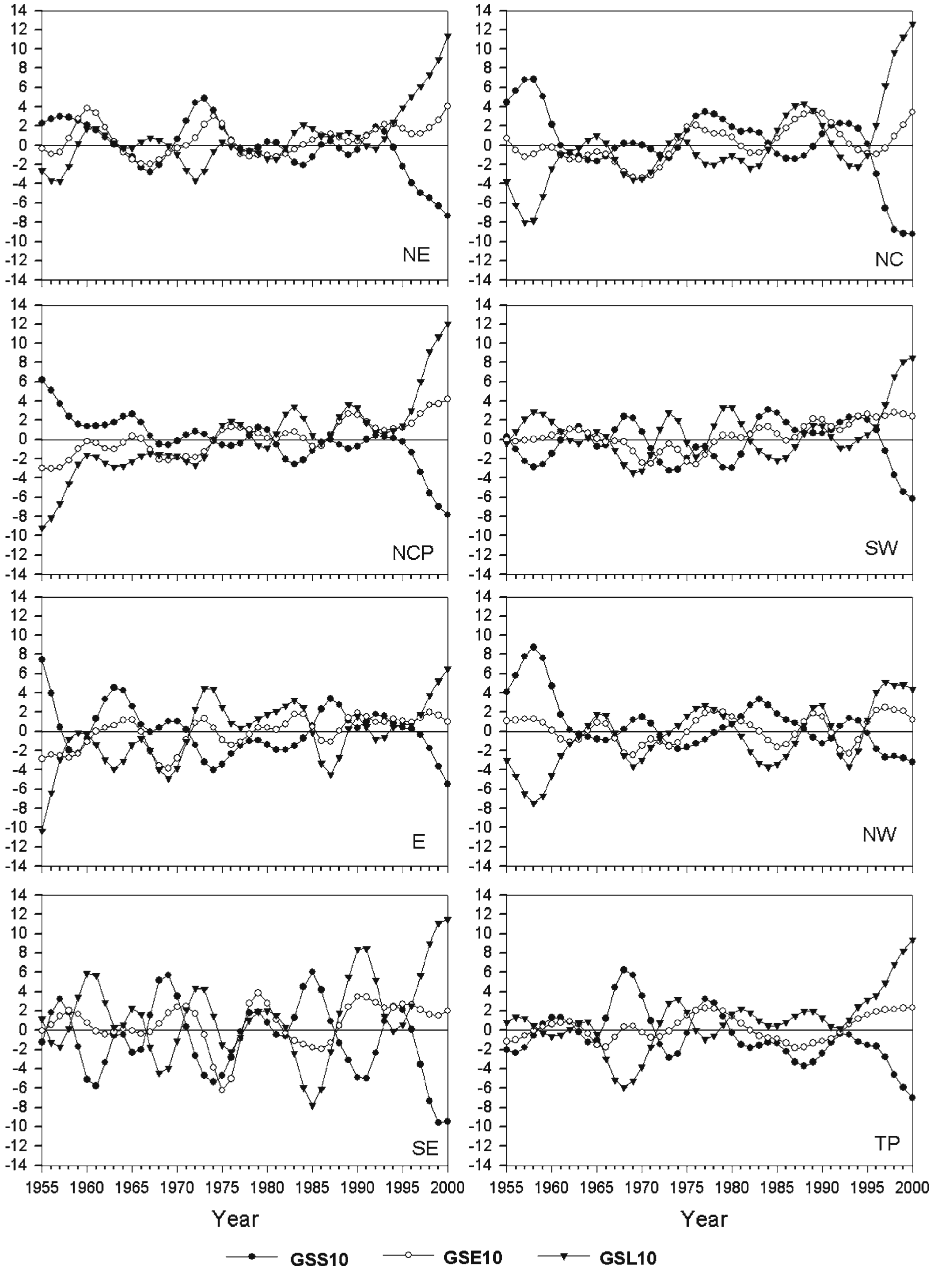


Fig. 11 Time series of regional averaged GSS, GSE, and GSL (>10°C) anomalies (from the 1961–1990 mean). The values have been smoothed with a 9-year binomial filter with reflected ends

cases is evident from the average conditions in these climatic regions (see Table 2), when GSL for a given base temperature comprises nearly the entire calendar year. In Southeast China, temperatures rarely if ever drop below freezing, and the dates of GSS and GSE for the 0°C base temperature were taken to be 1 January and 31

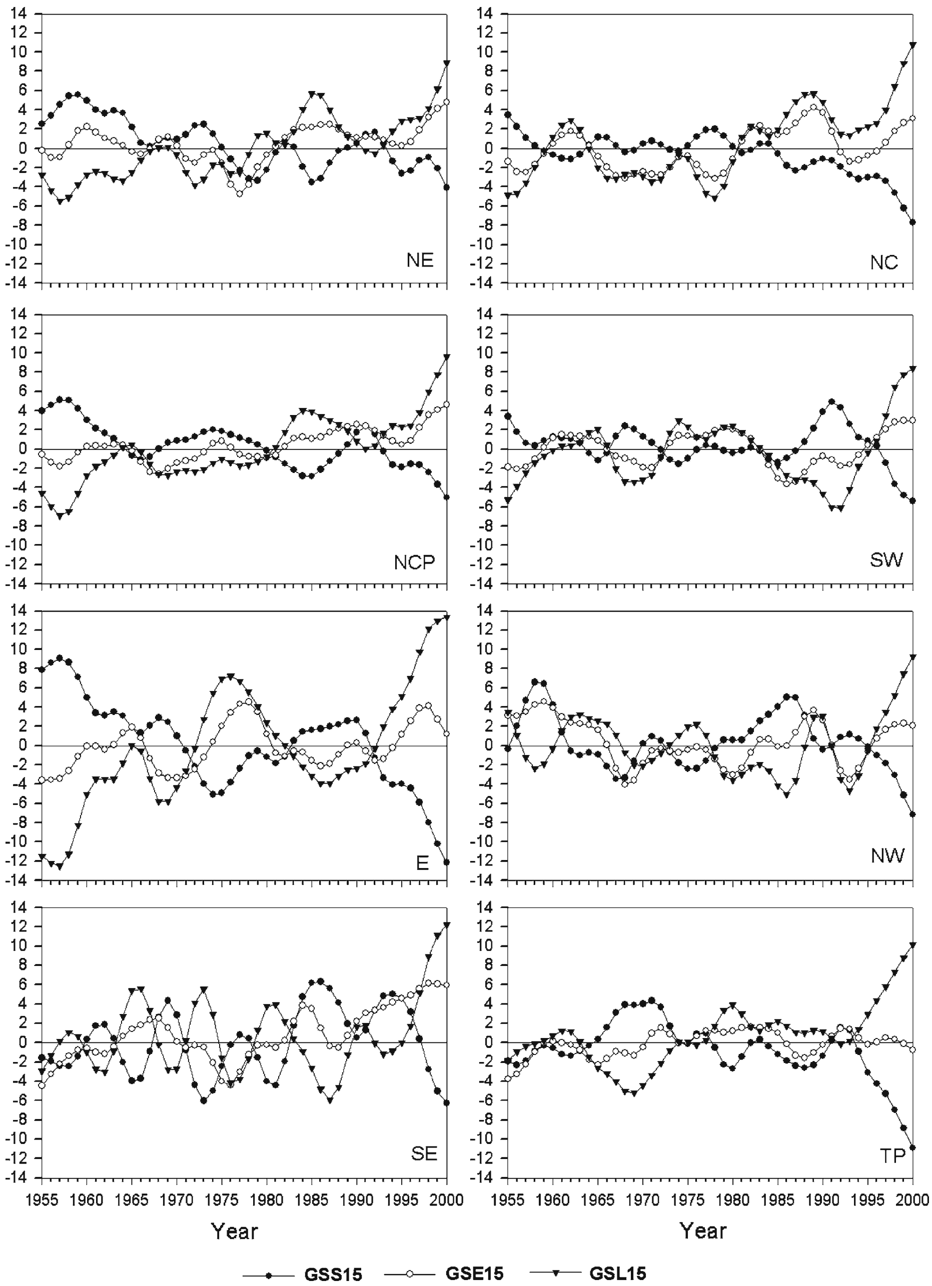


Fig. 12 Time series of regional averaged GSS, GSE, and GSL (>15°C) anomalies (from the 1961–1990 mean). The values have been smoothed with a 9-year binomial filter with reflected ends

December respectively. Under these conditions, increasing temperatures can result in little or no change to these regions' climatic growing season. In other words, the growing season, except its intensity, is saturated in this area.

Figure 13 shows the time series of national average GDD for the four base temperatures. Again, we observe two distinct regimes: an initial period of moderate fluctuations around the base period average GDD, followed by a period of rapidly increasing GDD. For this climatic indicator, the turning point for all four base temperatures is around 1985, with differences only in the magnitude of the change.

The regional time series of GDD for the four base temperatures appear in Fig. 14. Similar to the national series, we also see two distinct regimes in the series for the eight climatic regions and four base temperatures. For each climatic region, the turning points for the different base temperatures are almost identical. The temporal pattern of this indicator, though, differs from that seen for GSL. Thus in Southeast China, where no change in GSL (>0°C) is observed from1955 to 2000, we nonetheless find a rapid increase in GDD (>0°C) from 1985 to 2000.

3.4 Relationships among the variables

The derived temperature indices are compared with spring-summer-autumn mean air temperatures (SSA Tmean) in Table 3. Nationally, we find that the GSS, GSE, GSL, and GDD time series are well correlated with the SSA Tmean time series (statistically significant at the 99% confidence level for all four base temperatures). Regionally, correlations between GDD and the SSA Tmean series are statistically significant at the 99% confidence level for all four base temperatures. Correlations with GSL are also significant except southeast China, southwest China and east China for the base temperatures of 0°C and southeast China for the base temperatures of 5°C. The correlation coefficients (*r*) for the relationship between GDD and SSA Tmean are uniformly higher than those for GSL. These results are similar to those documented in other countries. For the former Soviet Union, Jones and Briffa (1995) found that GDD (>5°C) was highly correlated with May–September temperatures at individual stations. In northern and central Europe, degree-day counts (>5°C) have been shown to be very strongly correlated with average temperatures for an extended summer period, but durations of the growing season are only weakly correlated with the appropriate extended seasonal temperatures (Jones et al. 2002).

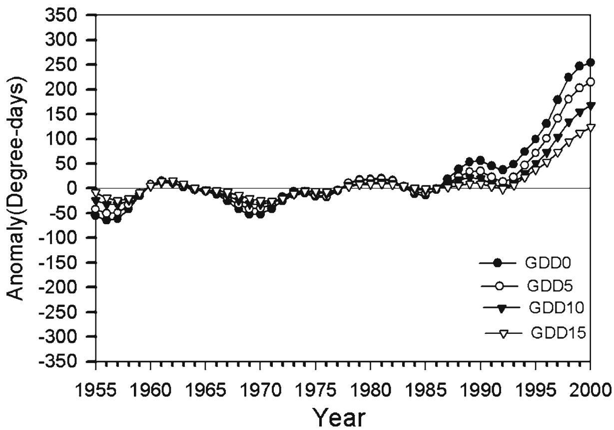


Fig. 13 Time series national averaged GDD anomalies (from the 1961–1990 mean). The values have been smoothed with a 9-year binomial filter with reflected ends

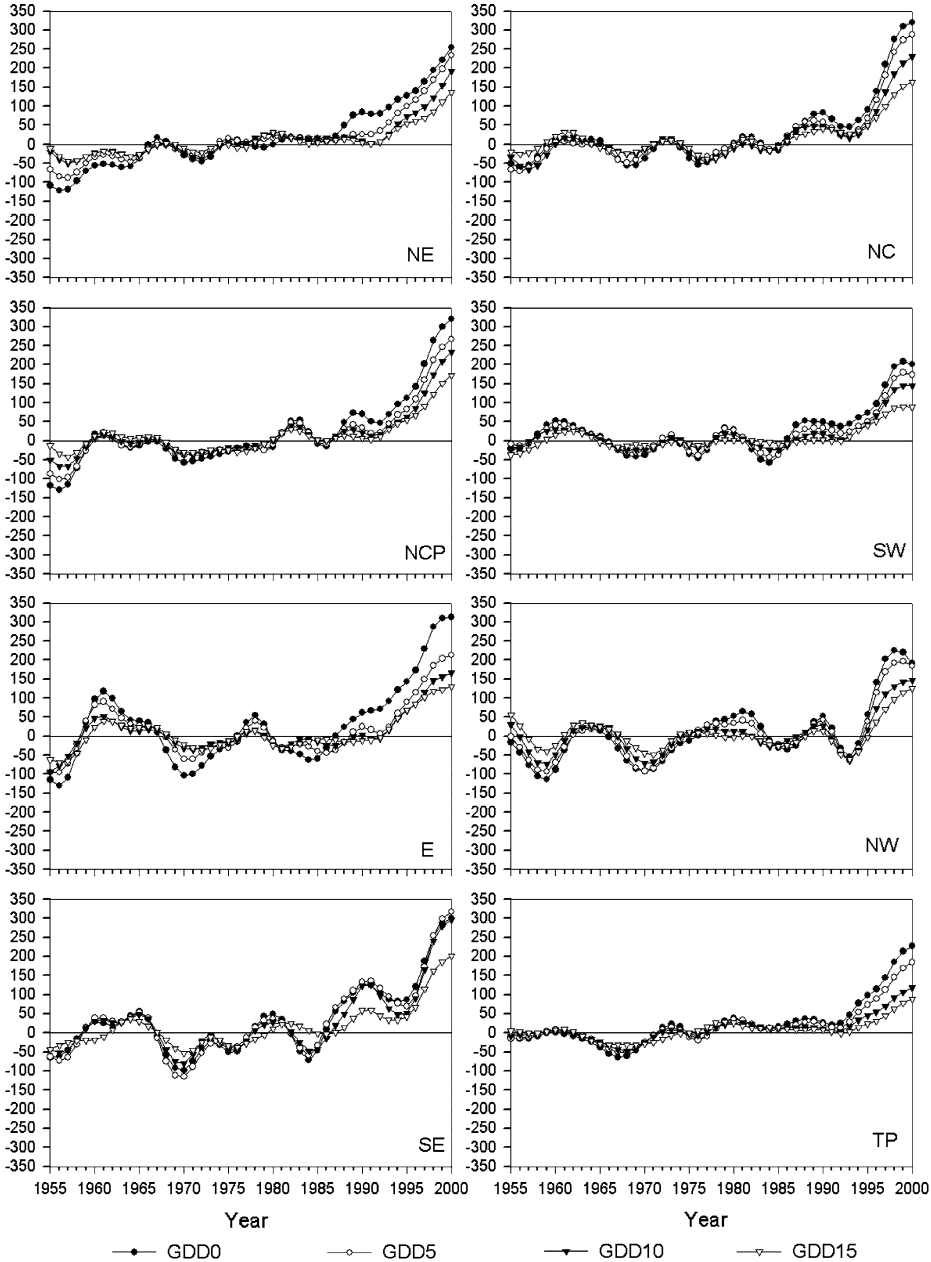


Fig. 14 Time series of regional GDD anomalies (from the 1961–1990 mean). The values have been smoothed with a 9-year binomial filter with reflected ends

Correlations between both GSS and GSE and the SSA Tmean are statistically significant at the 99% confidence level for all four base temperatures in north China, but not statistically significant in the southern and western regions for some of the

Table 3 Correlation coefficient (*r*) between average temperature (during March to November) and derived temperature indices

	GSS	GSE	GSL	GDD
Tmean above 0°C				
Northeast China (NE)	−0.75**	0.44**	0.74**	0.88**
North China Plain (NCP)	−0.76**	0.48**	0.83**	0.97**
East China (E)				0.76**
Southeast China (SE)				0.77**
North Central China (NC)	−0.37**	0.37**	0.56**	0.95**
Southwest China (SW)		0.37**		0.78**
Northwest China (NW)	−0.49**	0.58**	0.78**	0.90**
Tibetan Plateau (TP)	−0.53**	0.60**	0.73**	0.93**
Nationwide	−0.59**	0.53**	0.75**	0.86**
Tmean above 5°C				
Northeast China (NE)	−0.65**	0.47**	0.73**	0.80**
North China Plain (NCP)	−0.68**	0.46**	0.79**	0.93**
East China (E)			0.30*	0.90**
Southeast China (SE)				0.68**
North Central China (NC)	−0.40**		0.38**	0.85**
Southwest China (SW)		0.28	0.40**	0.84**
Northwest China (NW)	−0.48**	0.51**	0.75**	0.82**
Tibetan Plateau (TP)	−0.55**	0.59**	0.75**	0.88**
Nationwide	−0.55**	0.67**	0.81**	0.86**
Tmean above 10°C				
Northeast China (NE)	−0.54**	0.28	0.60**	0.62**
North China Plain (NCP)	−0.65**	0.48**	0.77**	0.86**
East China (E)	−0.41**		0.46**	0.93**
Southeast China (SE)	−0.27		0.33*	0.81**
North Central China (NC)	−0.34*		0.39**	0.79**
Southwest China (SW)	−0.45**	0.32*	0.58**	0.94**
Northwest China (NW)	−0.41**	0.25	0.49**	0.78**
Tibetan Plateau (TP)	−0.61**		0.67**	0.72**
Nationwide	−0.63**	0.56**	0.78**	0.86**
Tmean above 15°C				
Northeast China (NE)	−0.34*	0.32*	0.45**	0.59**
North China Plain (NCP)	−0.46**	0.42**	0.54**	0.76**
East China (E)	−0.41**	0.26	0.49**	0.80**
Southeast China (SE)	−0.48**		0.51**	0.92**
North Central China (NC)	−0.39**	0.48**	0.56**	0.73**
Southwest China (SW)	−0.35*	0.40**	0.47**	0.86**
Northwest China (NW)	−0.48**		0.51**	0.76**
Tibetan Plateau (TP)	−0.58**		0.53**	0.57**
Nationwide	−0.39**	0.59**	0.67**	0.75**

Coefficients without asterisks were significant at $P = 0.10$; coefficients not shown were not significant at $P \leq 0.10$

$^{*}P = 0.05$, $^{**}P = 0.01$

base temperatures. Either the start date or end date of growing season, or both, can influence the length of the growing season. We performed a regression analysis to measure the relative influences of GSS and GSE on GSL. Table 4 shows the R^2 values for China as a whole and for the eight climatic regions. Nationally, GSS has the higher R^2 values; thus, the start date of growing season appears to have the

Table 4 R^2 values for simple linear regression models predicting the length of the growing season, 1955–2000

	Independent Variables	
	Start of growing season	End of growing season
Tmean above 0°C		
Northeast China (NE)	0.74*	0.66*
North China Plain (NCP)	0.76*	0.42*
East China (E)	0.88*	0.03
Southeast China (SE)	1.00*	0.00
North Central China (NC)	0.50*	0.48*
Southwest China (SW)	0.90*	0.00
Northwest China (NW)	0.41*	0.59*
Tibetan Plateau (TP)	0.71*	0.53*
Nationwide	0.70*	0.44*
Tmean above 5°C		
Northeast China (NE)	0.62*	0.51*
North China Plain (NCP)	0.70*	0.40*
East China (E)	0.60*	0.41*
Southeast China (SE)	0.94*	0.00
North Central China (NC)	0.55*	0.42*
Southwest China (SW)	0.70*	0.14*
Northwest China (NW)	0.57*	0.49*
Tibetan Plateau (TP)	0.58*	0.52*
Nationwide	0.67*	0.48*
Tmean above 10°C		
Northeast China (NE)	0.64*	0.44*
North China Plain (NCP)	0.69*	0.58*
East China (E)	0.61*	0.45*
Southeast China (SE)	0.79*	0.03
North Central China (NC)	0.71*	0.33*
Southwest China (SW)	0.52*	0.34*
Northwest China (NW)	0.64*	0.36*
Tibetan Plateau (TP)	0.66*	0.00
Nationwide	0.75*	0.41*
Tmean above 15°C		
Northeast China (NE)	0.65*	0.35*
North China Plain (NCP)	0.65*	0.61*
East China (E)	0.66*	0.42*
Southeast China (SE)	0.55*	0.34*
North Central China (NC)	0.55*	0.53*
Southwest China (SW)	0.69*	0.39*
Northwest China (NW)	0.56*	0.21*
Tibetan Plateau (TP)	0.46*	0.13*
Nationwide	0.74*	0.33*

Asterisks (*) indicate statistical significance at 0.01 level

greater influence on the length of the growing season. Region by region, we find similar relationships except in northwest China for the base temperature of 0°C.

Comparisons of GSL with GDD can be seen in Table 5. We find that correlations between the GSL and GDD time series are statistically significant at the 99% confidence level for all four base temperatures, both nationally and regionally, with the one exception of southeast China at the base temperature of 0°C. (As noted above, temperatures rarely drop below the 0°C threshold in that climatic region, and

Table 5 Correlation coefficient (r) between growing degree-days (GDD) and growing season length (GSL)

	Tmean ≥ 0°C	Tmean ≥ 5°C	Tmean ≥ 10°C	Tmean ≥ 15°C
Northeast China (NE)	0.71**	0.64**	0.70**	0.67**
North China Plain (NCP)	0.82**	0.75**	0.79**	0.53**
East China (E)	0.69**	0.56**	0.49**	0.59**
Southeast China (SE)		0.54**	0.74**	0.69**
North Central China (NC)	0.50**	0.54**	0.59**	0.78**
Southwest China (SW)	0.59**	0.74**	0.72**	0.54**
Northwest China (NW)	0.66**	0.74**	0.70**	0.72**
Tibetan Plateau (TP)	0.73**	0.78**	0.73**	0.77**
Nationwide	0.79**	0.85**	0.82**	0.77**

Asterisks indicate significance as in Table 3

thus GSL there remains constant over time.) We also calculated correlations between GSL and GDD time series at individual stations, finding statistically significant correlations at the 95% confidence level at 80%, 91%, 95%, and 96% of the 305 stations for the base temperatures of 0°C, 5°C, 10°C, and 15°C, respectively. In this case, our results differ from most previous studies conducted elsewhere. Jones and Briffa (1995) found very low correlations between these series in the former Soviet Union. GSL was weakly correlated with degree-day counts in northern and central Europe, which Jones et al. (2002) interpreted to mean that warmer growing seasons need not necessarily be longer or shorter. Similar research in Nordic countries showed only a weak positive relationship between length and intensity of growing season (>5°C) at Fennoscandian sites, but at Stykkishólmur, Iceland, a long growing season is commonly associated with a high effective temperature sum (Carter 1998)—as we see in China. Our results show that at most climate stations in China over the latter half of the twentieth century, warmer growing seasons were also the longer growing seasons.

4 Summary and conclusions

In this paper we have concentrated on the spatial and temporal characteristics of the change in the climatic growing season in China over the second part of the last century, a period where climate trends have been dominated by the effects of anthropogenic global warming. National averaged GSS has become earlier by 4.6–5.5 days, GSE has become later by about 1.8–3.7 days, and GSL has become longer by about 6.9–8.7 days over this period, depending on the base temperature used. The spatial characteristics of the changes in these variables differ from those of change in temperature. The time series of these variables each appear to fall into two distinct regimes, consisting of an initial period of fluctuations around the base period average, followed by rapid change with earlier GSS, later GSE, and increased GSL. The turning point between these regimes comes earlier for lower base temperatures than for higher base temperatures. The same patterns obtain for nearly all regions and base temperatures examined.

National averaged GDD has become higher by 74.9 to 196.8 degree-days over the past 46 years, depending on the base temperature chosen. The spatial pattern of the change in GDD resembles that of change in temperature, with higher rates of change in the north. The GDD time series also can be divided into two distinct regimes, with a period of fluctuations around the base period before 1985 and a period of rapid increase from 1985 to 2000. For this variable, the turning point is consistent across the four base temperatures examined; they only differ in the in magnitude of change.

GDD and the spring-summer-autumn average temperature are highly correlated both at the national level and for all the climatic regions. GSL and SSA Tmean are highly correlated nationally and for all climatic regions except in east southeast and southwest China at base temperature of 0°C and southeast China at base temperature of 5°C. The start date of growing season appears to have the greater influence on the length of the growing season. Contrary to most reports from other countries, warmer growing seasons in China are significantly likely to be longer growing seasons.

Factors in the physical environment that affect the growth and development of plants are radiation, temperature, water and nutrients (Atkinson and Porter 1996). Three of these four factors are climatic. The biotic response to 30 years of enhanced global warming has become perceptible and substantial, as an overwhelming number of studies provide evidence for climate change impacts on species, communities, and ecosystems (Walther 2003). In analyzing the spatiotemporal trends of China's climate record, we have aimed to clarify some of the implications of climate change for agriculture and forestry. As our results indicate, patterns of change in China may differ from those reported elsewhere, and there are also important regional differences within China. These findings should spur further efforts to ameliorate the effects of climate change where possible and to develop adaptive strategies as necessary for the sustainable development of the agriculture and forestry sectors.

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