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Response of the starting dates and the lengths of seasons in Mainland China to global warming

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Abstract The climatic seasons in China, defined by station-specific daily temperature measures, have changed substantially during the past decades. In the majority of the country, the length of summer has extended and the length of winter has shortened since the 1950s. These changes in the lengths of seasons are linked to the changes in the starting dates of seasons. Namely, the starting date of summer has advanced and the starting date of winter has shifted back. Averaged across the whole country, the starting date of summer has been brought forward by 5.8 days and the season has extended 9 days. On the other hand, the starting date of winter has been delayed by 5.6 days and the season has shortened by 11 days. The changes for spring and fall are relatively smaller. Particularly, spring has started earlier by 5.7 days but shortened by 0.3 day, and fall has started later by 3.2 days but lengthened by 2.3 days. The changes in seasons exhibit apparent regional differences. They are more significant in the north than in the south where the trend of some local changes in seasons is opposite to that of the rest of the country.

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1 Introduction

In recent years, global warming has attracted much attention from the governments, general public, and scientific and social communities over the world. There are several reasons for this broad interest in global warming. Firstly, the global temperature, measured by both direct observations and credible proxy data, has risen exponentially in the recent hundreds of years. The fourth assessment report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) indicates that the global-average surface temperature has increased, especially since the 1950s, and the updated 100-year (1906–2005) trend of 0.74 ± 0.18°C is larger than the 100-year warming trend of the time of the third assessment report (1901–2000) of 0.6 ± 0.2°C due to additional warm years (Houghton et al. 2001; IPCC 2007). Secondly, the potential impacts of global warming on human beings, the environment, and economic and social developments have urged the scientific and social communities to improve the understanding of many issues of global warming such as its causes and the degree of significance of its impacts.

The response of the regional climate in China to global warming has also aroused much research interest (e.g., Shen 2001; Chen and Zhang 2001; Josep and Iolanda 2001; Sha et al. 2002; De Viron et al. 2002; Spagnoli et al. 2002; Ye et al. 2003a, b). Previous studies have linked the changes in the regional climate such as the increase in the mean and regional China temperature to global warming (Ye et al. 1991, 2001; Ye and Fu 1995; Ye and Lin 1995; Ye and Lu 2000; Fu et al. 2003). As reported by Wang and Ye (1995) and Ding and Dai (1994), the mean China temperature has risen 0.5–1.0°C during the past decades. At present, this mean temperature is widely used to understand the response of the regional climate to global warming.

Previous studies have applied different variables and approaches to understand different aspects of global warming and its climate impacts. Generally, one variable may provide a more succinct and clearer description of a specific aspect than others, while the other variables may have their own advantages for describing some other aspects of global warming and its impacts. That is, one expression may reflect the same phenomenon associated with global warming better than another does under different circumstances. For example, when describing the dry and wet state of the air, a variety of humidity variables such as relative humidity, absolute humidity, and specific humidity can be applied alternatively based on the purpose of analysis and the availability of data.

In this study, we develop a new expression that is different from the traditional approach to investigate the response of China regional climate to global warming. At least in the field of meteorology, December, January and February are conventionally defined as winter; March, April and May as spring; June, July and August as summer, and September, October and November as fall. Here, we present a definition of seasons based on temperature criterion, which is able to objectively and dynamically depict the changes in the starting dates and the lengths of seasons as a response to global warming. While the conventionally-defined seasons are fixed in time for all locations, the redefined seasons can reflect the nature of season variations in both starting points and durations associated with temperature changes, both seasonally and interannually, from one location to another. If there were no global warming, one might find only small differences between the two definitions. However, because the warming of the climate system is unequivocal, as summarized in AR4 of IPCC, the conventional definition of seasons may no longer provide a real timing concept of temperature since it lacks the inclusion of climate change information (IPCC 2007). Thus, the new definition (see more details in the next section) is able to describe an overall impact of global warming. Discussions of several examples with a simple and subjective definition of seasons for Beijing (northern China), Lanzhou (northwestern China), and Hailar (northeastern China) have been given in Ye et al. (2003b).

The definition of seasons given in this study yields information about the timing of seasons associated with global warming, which is useful for crop planting, risk management, health care, disease control, disaster protection, and other applications. For example, although the IPCC AR5 indicates that the global mean temperature has increased about 0.74°C from 1906 to 2005, one may not be able to easily assess the impact of this amount of temperature change. On the contrary, one may benefit more if the change in temperature is conversed to the information about the change in season length, which affects planting, clothing, and other daily activities. Also, certain parameters such as the number of frost free days are important for studies of the impact of climate change on agriculture and others; however, the lengths of seasons defined by temperature changes provide useful information for planting, animal migration, and the daily life of human being, since they are closely related to seasons defined by temperature.

In the next section, we describe the data and methodology. We analyze the observations of daily temperature over mainland China for the time period of 1950–2000. In Section 3, we present the main features of the results obtained. In particular, we discuss the statistical features of changes in seasons, the spatial differences in the starting dates of and the lengths of seasons. A summary of the results obtained is provided in Section 4.

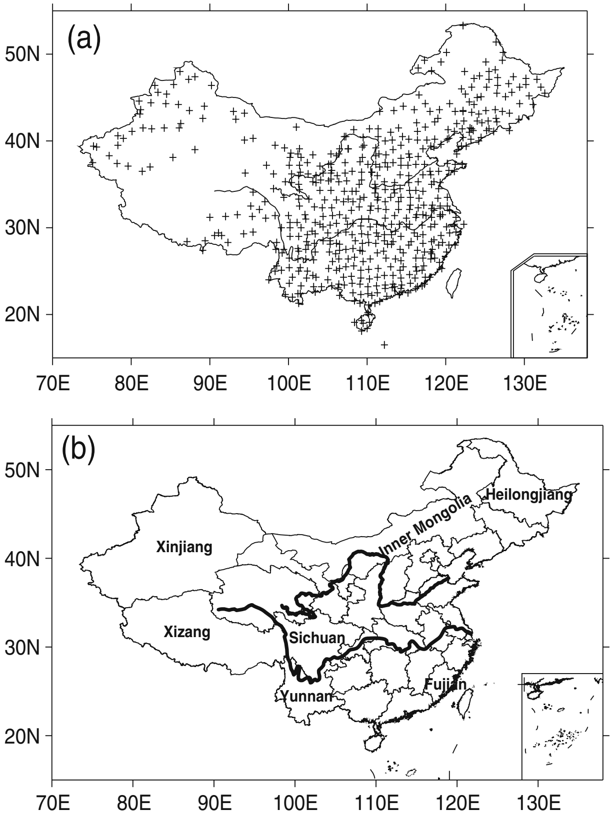
2 Data and methodology

In this analysis, we apply the temperature data of 4 times per day compiled by the China Meteorological Administration. The dataset contains the surface temperature of 732 Chinese stations, covering the time period of 1951–2000. We define daily mean temperature as the averaged value of four observations of the day:

$$T_{ijk} = \frac{1}{4}\sum_{m=1}^{4} T_{ijk}^{m}, \tag{1}$$

where T_{ijk} and T_{ijk}^{m} represent, respectively, the daily mean temperature and the mth observation of temperature at the ith station on the kth day in the jth year, $m \in [1,4]$, $i \in [1,732]$, $j \in [1950,2000]$, and $k \in [1,365]$ for non-leap years or $k \in [1,366]$ for leap years. A nine-point smoother is applied to remove the short-term perturbations of temperature. Although most of the 732 stations have continuous observations, exceptions occur to some stations. We exclude the stations whose continuous observations are less than 45 years from our analysis and retain only 612 stations in the computations. Figure 1a illustrates the geographic locations of the 612 stations, in which longitudes range from 75.14° E to 132.58° E and latitudes from 16.5° N to 53.28° N. The elevations of these stations range from 2.2 to 4,701 m above the sea level, with a mean of 864.1 m. To facilitate later discussions, we show

Fig. 1 Maps showing (**a**) the distribution of 612 Chinese stations and (**b**) the locations of several provinces that are discussed in the text. The locations of the Yellow River in the north and the Yangtze River in the south are also shown in the maps



the locations of the Yellow River and the Yangtze River, as well as the locations of several provinces of China that will be referred to, in Fig. 1b.

As mentioned above, the seasons of spring, summer, fall, and winter are conventionally referred to March–May, June–August, September–November, and December–February, and thus seasonal warming or cooling is usually discussed based on these fixed seasons. Here, we define seasons and the changes in seasons by temperature criteria. We use the terms of advancing or retarding and lengthening or shortening of seasons to describe the changes in seasons. Specifically, we define the coldest quarter of a year in the long-term (1951–2000) means as winter and the warmest quarter as summer. The quarter between winter and summer is then referred to as spring and the quarter between summer and winter is referred to as fall.

2.1 Long-term averages of daily mean temperature

For each station, we compute the long-term average of the daily mean temperature as

$$T_{ik} = \frac{1}{J}\sum_{j=1}^{J} T_{ijk},\ i \in \left[1{,}612\right],\ k \in \left[1{,}365\right],\ j \in [1, J] \text{ and } J \in \left[45{,}51\right]. \tag{2}$$

In the equation, T_{ik} denotes the long-term average temperature at the ith station on the kth day. For convenience of analysis, we let $k = 1, 2, \ldots, 365$. That is, the last day of leap years is not considered.

2.2 Temperature criteria for starts of seasons

We use T^i_{ss}, T^i_{sf}, T^i_{fw}, and $T^i_{ws}$to denote the temperature criteria of the ith station, for which spring is differentiated from summer, summer from fall, fall from winter, and winter from spring, respectively. The criteria satisfy the following relations:

$$\begin{cases} D^i_{sk} = \begin{cases} 1, & T_{ik} > T^i_{ss}, \\ 0, & T_{ik} \le T^i_{sf}, \end{cases} \\ \sum\limits_{k=1}^{365} D^i_{sk} = 91, \\ D^i_{wk} = \begin{cases} 1, & T_{ik} < T^i_{fw}, \\ 0, & T_{ik} \ge T^i_{ws}, \end{cases} \\ \sum\limits_{k=1}^{365} D^i_{wk} = 91, \\ T^i_{ss} = T^i_{sf}, \\ T^i_{fw} = T^i_{ws}. \end{cases} \tag{3}$$

2.3 Starting dates and lengths of seasons

The starting dates of spring, summer, fall, and winter (D^{spr}_{ij}, D^{sum}_{ij}, D^{fal}_{ij}, andD^{win}_{ij}) of the jth year at the ith station are determined by using the T_{ijk} data series of the jth year and the seasonal temperature criteria (T^i_{ss}, T^i_{sf}, T^i_{fw}, and T^i_{ws}) of the ith station. However, in practice, the average operation should be applied to the multiple solutions resulted from the temperature perturbations of synoptic scales. The lengths (numbers of days) of spring, summer, fall, and winter of the jth year at the ith station (L^{spr}_{ij}, L^{sum}_{ij}, L^{fal}_{ij}, and L^{win}_{ij}) are calculated using the following expressions:

$$\begin{cases} L^{spr}_{ij} = D^{sum}_{ij} - D^{spr}_{ij}, \\ L^{sum}_{ij} = D^{fal}_{ij} - D^{sum}_{ij}, \\ L^{fal}_{ij} = D^{win}_{ij} - D^{fal}_{ij}, \\ L^{win}_{ij} = 365 - \sum\limits_{sea=spr}^{fal} L^{sea}_{ij}. \end{cases} \tag{4}$$

We summarize the methodology of our analysis for each of the 612 stations in the following three steps:

Step 1 We first compute the climatological mean daily temperature for the 50 entire years, obtaining 365 values measuring the climatological mean annual cycle.

Step 2 We compute the transitional temperatures for the four seasons based on the time series obtained from Step 1. For climatological conditions, we define the warmest 91 days as summer season and the coldest 91 days as winter season. Under this definition, the time period between winter and summer is spring, and the time period between summer and winter is fall.

Thus, we are able to determine the values of temperature of the transitional point between any two seasons based on Eq. 3 and the assumption that the temperature of the starting of summer (winter) is equal to the temperature of the ending of summer (winter). It should be pointed out that the values of temperature of the transitional points of seasons vary from station to station.

Step 3 We then apply the climatological values of temperature of transitional points obtained above to determine the lengths of seasons for each of the 50 years. Because temperature changes from one year to another, the lengths of summer and winter of individual years can be different from the climatological value of 91 days and thus the lengths of spring and fall can be different from the climatology as well.

2.4 Linear trends

The least-squares method is employed to determine the linear trends of the above eight (dependent) variables (D_{ij}^{spr}, D_{ij}^{sum}, D_{ij}^{fal}, D_{ij}^{win}, L_{ij}^{spr}, L_{ij}^{sum}, L_{ij}^{fal}, and L_{ij}^{win}) over the last 50 years:

$$\begin{cases} \tilde{Y}_{ij} = aj + b\,, \\ \lim\limits_{a \to a_0, b \to b_0} \sum\limits_{j=1}^{J_i} \left(\tilde{Y}_{ij} - Y_{ij} \right)^2 \to Min, \end{cases} \tag{5}$$

where $\tilde{Y}_{ij}$ represents the fitting value of Y_{ij}, and J_i the length (number of years) of the data at ith station. a_0 and b_0 are fitting coefficients, and the multiplication of a_0 by 50 yields the linear trend of Y_{ij} in the last 50 years. The size of Min reflects the deviation extent of the linear fitting series $\tilde{Y}_{ij}$ from the observed data series Y_{ij}.

3 Result analysis

3.1 Statistical features of changes in seasons

On average, the starts of spring and summer have become earlier by 5.7 and 5.8 days from 1951 to 2000, while the starts of fall and winter have become later by 3.2 and 5.6 days, respectively. The duration of season has extended by 9 days for summer and 2.3 days for fall. However, winter has shortened by 11 days. Although spring has started earlier, the length of the season remains little changed (shortened by 0.3 day only), because summer has advanced as well.

The changes in seasons over China show distinctive regional differences. Although the spring and summer seasons have advanced (in the last 50 years) as a whole and in some locations over Xizang (western China) the seasons have started earlier by more than 40 days for spring and even more for summer, in other places of Xizang and Yunnan (southwestern China) spring and summer have started later by 26 and 32 days, respectively. Similarly, although the starts of fall and winter have been generally delayed, the fall season has advanced by 31 days at Tuerduote of Xinjiang and advancement of winter can also be found over some regions. Large regional differences exist in the changes in the lengths of seasons as well. We will discuss these regional features of changes in seasons in the next subsections.

3.2 Regional features of changes in start of seasons

Figure 2 displays the changes in the starting days of spring, summer, fall, and winter from 1951 to 2000. As seen from Fig. 2a, negative values appear in a large part of China, indicating advancement of the spring season. The most remarkable advancements occur in northeastern China, where the season has advanced by more than 10 days, and the northeast of the Tibetan plateau. The spring season has also advanced by more than 10 days in the upper reaches of the Yangtze River and the Yellow River. On the other hand, the start of spring season has been slightly delayed in south of the Yangtze River.

Figure 2b shows the changes in the starting dates of summer season, which has advanced clearly over more than 70% of China. The most evident advancements are seen over Xinjiang (northwestern China), the Great Bend of the Yellow River, northern-northeastern China, and some coastal regions. However, in some small areas of the Yangtze-Huaihe River valley, central China, and the middle–upper reaches of the Yellow River, the start of summer has been delayed slightly and more analyses are needed to understand the reason for this feature.

Compared to spring and summer, the start of fall has become later over 60% areas of China (Fig. 2c). The trend of the starting date of fall shows a clear spatial pattern. There exists a northwest-southeast oriented zone, from Xinjian in the northwest to Fujian in the southeast, where the season is characterized by a slightly earlier start. On its both sides, the starts of fall have been delayed. The largest delay occurs near the Tibetan plateau and over northern-northeastern China, by more than 10 days in some places.

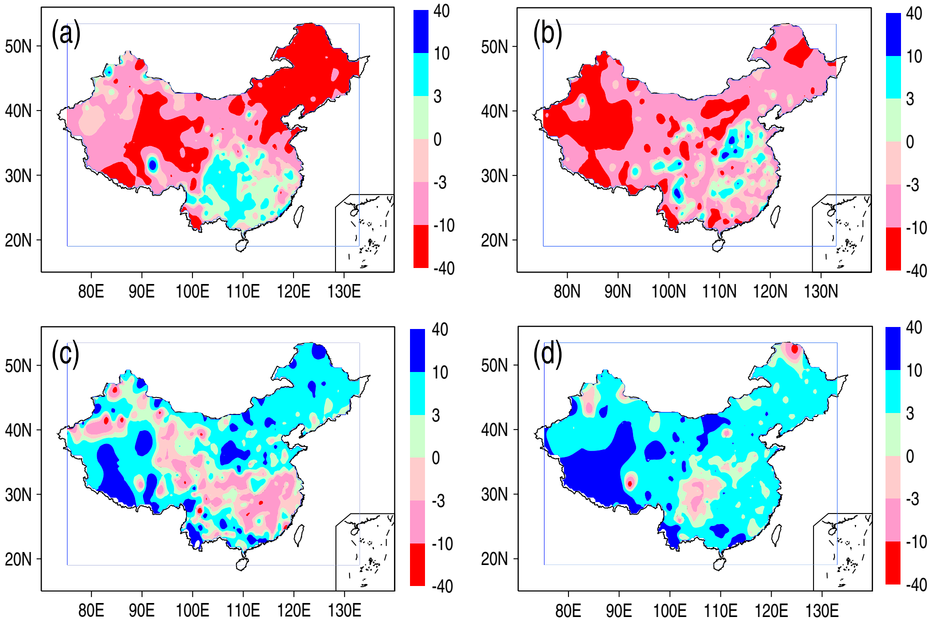


Fig. 2 Changes in the starting dates of climatic seasons from 1951 to 2000 for spring (**a**), summer (**b**), fall (**c**), and winter (**d**). *Negative values* denote advances of seasons, and *positive values* represent delays of seasons. Units: days

Winter is characterized by a most significant delay in the start of season from 1951 to 2000 (Fig. 2d), compared to the other seasons. The regions of most remarkable delay include the Southwest, east of the Tibetan plateau, west of Inner Mongolia, and some coastal areas over southern China. In some places, the start of winter has been delayed by more than 10 days. Only in some small areas including the Sichuan Basin has the winter season advanced slightly.

3.3 Regional features of changes in lengths of seasons

The change in the length of spring season in the last 50 years is given in Fig. 3a. It can be seen that the areas of lengthening and shortening of the season are roughly equal. The most prominent lengthening appears over northeastern China and from the middle and lower reaches of the Yellow River to the Yangtze-Huaihe River valley. In some of these places, the length of spring has increased by more than 10 days. Extension of spring season can also be seen over the Tibetan plateau, especially its eastern portion. However, spring season has shortened in over southern and northwestern China and over the Great Bend of the Yellow River.

A nearly countrywide extension of season from 1951 to 2000 occurs in summer (Fig. 3b). The most remarkable summer lengthening is seen over northern and western China. Over the Tibetan plateau and the Great Bend of the Yellow River, the length of summer has increased by more than 20 days, although mixed signals appear over the southern portion of central-eastern China where slight shortening of summer occurs in some locations.

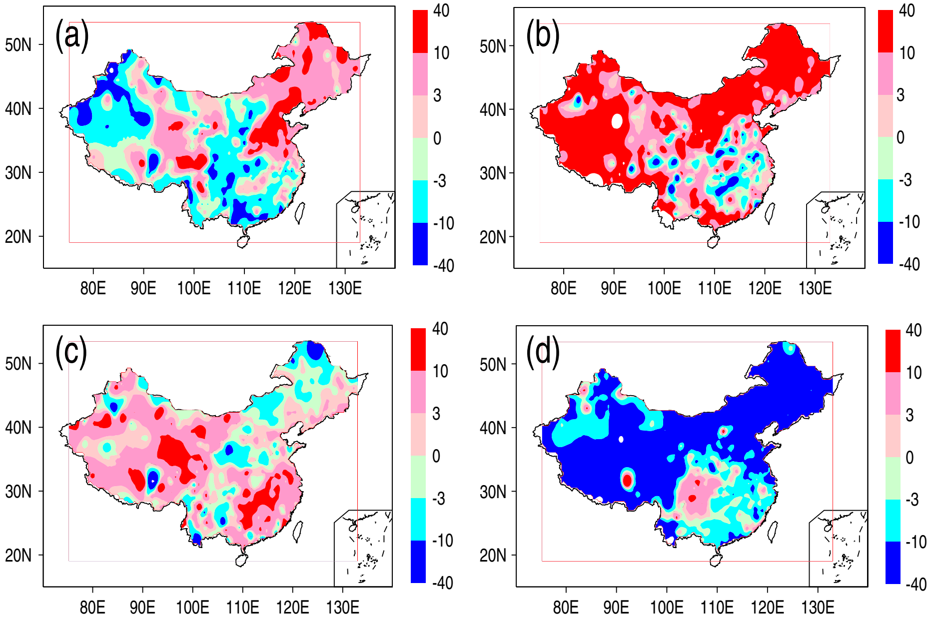


Fig. 3 Changes in the lengths of climatic seasons from 1951 to 2000 for spring (**a**), summer (**b**), fall (**c**), and winter (**d**). *Positive values* denote the lengthening of seasons, and *negative values* represent the shortening of seasons. Units: days

For fall (Fig. 3c), over a large part of China including south of the Yellow River (east of 108°E) and western China, the season has lengthened from 1951 to 2000. Especially over central China and the Tibetan plateau, it has extended by more than 10 days. The pattern of Fig. 3c is also characterized by a northeast-southwest oriented zone from Heilongjiang in the northeast to Yunnan in the southwest, in which the dry and unstable climate has shortened slightly. It is known that the special ecological zone between the western pasturing land and the eastern farming land of China, so-called “agro-pastoral ecotone”, experiences a variety of climate features. Climatologically, it is a transition zone from the dry climate in the west to the wet climate in the east. The above-mentioned northeast-southwest oriented zone largely corresponds to this vulnerable zone of the climate ecosystem and, apparently, the change in fall is linked to the vulnerable ecological environment.

The most significant shortening of seasons in China occurs in winter. It can be seen from Fig. 3d that the length of winter season has shortened apparently over most of the country. Over northeastern China, the Tibetan plateau, and northwestern China, the season has shortened by more than 20 days. Only over the Sichuan Basin and its peripheral areas has the winter season lengthened by 3–7 days, which is consistent with the decrease in temperature over southwestern China (Sha et al. 2002; also see discussion later).

We further examine the trends of changes in surface temperature for the various seasons. Figure 4 indicates that, from 1951 to 2000, temperature has risen clearly over

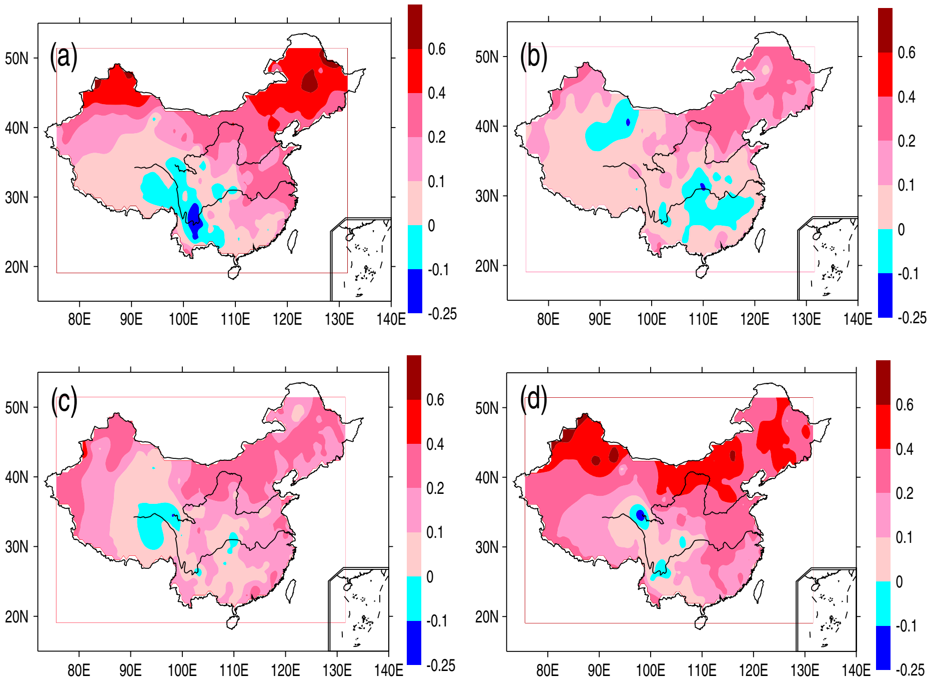


Fig. 4 Trends in seasonal-mean surface temperature from 1951 to 2000 for spring (**a**), summer (**b**), fall (**c**), and winter (**d**). *Positive* (*negative*) values represent *increase* (*decrease*) in temperature. Unit: °C per 10 years

China and the most significant increase in temperature occurs in winter and spring. The increase in temperature takes place nearly countrywide. Over northeastern and western China, the temperature increases all year round. Central-eastern China also experiences a temperature increase in each season except summer (Fig. 4b). Only over the Sichuan Basin (southwestern China) has the temperature decreased in most of the seasons, explaining the unique local features of changes in the starting dates and the lengths of seasons as previously seen from Figs. 2 and 3.

4 Conclusions and discussion

In this study, we have investigated the changes in China regional climate from 1951 to 2000 using the daily temperature data at 612 meteorological stations. We have first defined new temperature criteria to determine climatic seasons, developed a new method to describe the changes in seasons using the temperature criteria, and investigated the response of the climate over China to global warming. The major results of the study are summarized as follows.

1. A definition of seasons that is based on temperature criterion and is able to depict the changes in the starting dates and the lengths of seasons as a response to global warming objectively and dynamically has been presented in this study. The seasons so defined are different from the conventionally-defined seasons, in which the new definition may measure the variations in both starting dates and durations of seasons associated with temperature changes, both seasonally and interannually, from one location to another.
2. In the last 50 years, the changes in the climatic seasons over China have responded apparently to global warming. On average, the summer season has lengthened by 5.8 days and winter has shortened by 5.6 days. The spring and summer seasons have clearly started earlier, but the starts of fall and winter have been delayed.
3. The changes in seasons show distinctive regional differences. In most of northern China, the summer season has advanced and become longer, while the winter season has been delayed and shortened in the last 50 years. Associated with these changes in summer and winter, spring has advanced and fall has delayed.
4. The trends of changes in seasons over the vicinity of the Sichuan Basin are opposite to those over most of the rest of China, due to the cooling trend in the Sichuan Basin. The changes in seasons are generally characterized by opposite trends between southern China and northern China.
5. The changes in seasons lead to changes in the growing and maturation periods of crops, as well as in decision making for risk management, health care, disease control, disaster protection, and other applications, an important issue that deserves further studies. An urgent need of research on season variations on the global scale is to better understand how the global-average seasons respond to the global warming.

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