Variations of the thermal growing season during the period 1961-2015 in northern China (Postprint)

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Date: 2018-02-28T00:00:00+00:00

Abstract

Researching into changes in thermal growing season has been one of the most important scientific issues in studies of the impact of global climate change on terrestrial ecosystems. However, few studies investigated the differences under various definitions of thermal growing season and compared the trends of thermal growing season in different parts of China. Based on the daily mean air temperatures collected from 877 meteorological stations over northern China from 1961 to 2015, we investigated the variations of the thermal growing season parameters including the onset, ending and duration of the growing season using the methods of differential analysis, trend analysis, comparative analysis, and Kriging interpolation technique. Results indicate that the differences of the maximum values of those indices for the thermal growing season were significant, while they were insignificant for the mean values. For indices with the same length of the spells exceeding 5°C, frost criterion had a significant effect on the differences of the maximum values. The differences of the mean values between frost and non-frost indices were also slight, even smaller than those from the different lengths of the spells. Temporally, the starting date of the thermal growing season advanced by 10.0–11.0 days, while the ending dates delayed by 5.0–6.0 days during the period 1961–2015. Consequently, the duration of the thermal growing season was prolonged 15.0–16.0 days. Spatially, the advanced onset of the thermal growing season occurred in the southwestern, eastern, and northeastern parts of northern China, whereas the delayed ending of the thermal growing season appeared in the western part, and the length of the thermal growing season was prolonged significantly in the vast majority of northern China. The trend values of the thermal growing season were affected by altitude. The magnitude of the earlier onset of the thermal growing season decreased, and that of the later ending increased rapidly as the altitude increased, causing the magnitude of the prolonged growing season increased correspondingly. Comparing the applicability of selected indices and considering the impacts of frost on the definitions are important and necessary for determining the timing and length of the thermal growing season in northern China.

Full Text

Preamble

Variations of the Thermal Growing Season During the Period 1961-2015 in Northern China

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Abstract: Investigating changes in the thermal growing season represents one of the most critical scientific issues in assessing the impacts of global climate change on terrestrial ecosystems. However, few studies have examined the differences arising from various definitions of thermal growing season or compared trends across different regions of China. Based on daily mean air temperature data from 877 meteorological stations across northern China from 1961 to 2015, we analyzed variations in thermal growing season parameters—including onset, ending, and duration—using differential analysis, trend analysis, comparative analysis, and Kriging interpolation. Results indicate significant differences in maximum values among these indices, while mean value differences remained insignificant. For indices with identical spell lengths exceeding 5°C, frost criteria exerted a significant effect on maximum value differences. The mean value differences between frost and non-frost indices were also slight, even smaller than those resulting from different spell lengths exceeding 5°C.

Temporally, the thermal growing season onset advanced by 10.0–11.0 days while ending dates delayed by 5.0–6.0 days during 1961–2015, resulting in a 15.0–16.0 day extension of season duration. Spatially, advanced onset occurred in southwestern, eastern, and northeastern northern China, delayed endings appeared in western regions, and significant length prolongation characterized the vast majority of the study area. Trend magnitudes were altitude-dependent: the rate of onset advance decreased with altitude, while the rate of ending delay increased rapidly at higher elevations, causing corresponding increases in season prolongation. Careful index selection and consideration of frost impacts are essential for determining thermal growing season timing and length in northern China.

Keywords: daily mean air temperatures; growing season length; thermal growing season starting date; thermal growing season ending date; trend; northern China

1 Introduction

Global-mean surface temperature records reveal a linear warming trend of 0.85°C during 1880–2012, with projected increases of 0.3°C–4.8°C for 2081–2100 relative to 1986–2005 (IPCC, 2013). This warming has shifted seasonal timing, causing earlier springs, later autumns, and earlier peak photosynthesis (Burrows et al., 2011; Barichivich et al., 2012; Xu et al., 2016), while extending growing season length (Piao et al., 2007; Wang et al., 2016). Changes in vegetation growing season affect ecosystem structure and function, agricultural production, and carbon sequestration potential, subsequently influencing global and regional climate (Linderholm, 2006; Piao et al., 2007; Mozafari and Torki, 2015; Wang et al., 2016). Consequently, investigating vegetation growing season changes has become a paramount scientific issue in global climate change and terrestrial ecosystem studies (Mozafari and Torki, 2015; Yang et al., 2016).

The thermal growing season represents the theoretical period when plant growth can occur—when temperature constraints are lifted and growth proceeds if other environmental requirements are met (Carter, 1998). It is typically expressed as the number of days with air temperatures exceeding a predefined threshold (Shen et al., 2012; Guo et al., 2016). For instance, Carter (1998) defined season start as daily mean temperature 5°C for more than 5 days and end as the 10-day running mean when daily temperature falls below 5°C. Dong et al. (2012) defined it as beginning on the last day of the first 6-day spell with daily mean temperature 5°C after the last spring frost, and ending on the first day of the first 10-day spell with mean temperature <5°C. Guo et al. (2016) used the last day of the first 5-day spell with daily mean temperature 5°C as start, and the last day of the first 5-day spell with mean temperature <5°C as end.

Under climate change, mean temperature shifts are expected to mirror growing season changes. However, climate-growing season relationships vary regionally, and no universal method applies broadly across all regions (Linderholm, 2006). Thermal growing season indices reflect climate change differently, and even minor definitional changes can yield distinctly heterogeneous results within the same region. Although several scholars have analyzed thermal growing season across China or its subregions (Song et al., 2010; Dong et al., 2012; Yang et al., 2013; Guo et al., 2016), few have conducted in-depth comparisons of growing season changes across different parts of China using various index definitions (Song et al., 2010). Therefore, this study aims to compare different definitions of thermal growing season parameters (starting date, ending date, and length) and analyze their variations and trends in northern China using daily mean air temperature data from 877 stations during 1961–2015.

2.1 Study Area

Northern China lies in the mid-latitudes of the Northern Hemisphere. This study encompasses regions north of 33°N, including Xinjiang, Inner Mongolia, Heilongjiang, Jilin, Liaoning, Hebei, Beijing, Tianjin, Shandong, Shanxi, Ningxia, most of Henan, Shaanxi, Gansu and Qinghai, and some northern portions of Jiangsu, Anhui, and Tibet (Fig. 1a [Figure 1: see original paper]). Strongly influenced by the East Asian monsoon, the area is predominantly characterized by arid and semi-arid climates, with summer (June–August) rainfall. Annual mean temperatures range from -4°C to 14°C, and annual precipitation varies from 25 to 1000 mm. The region features complex topography—including mountains, basins, plateaus, hills, and plains—and diverse biomes such as grasslands, farmlands, forests, deserts, and shrubs (Sun et al., 2015).

2.2 Data Collection

Daily mean air temperature data were used to calculate growing season parameters (starting date, ending date, and length). These data were obtained from the National Meteorological Information Center, China Meteorological Administration, covering 1951-2015. A total of 1218 surface weather observation stations were available in northern China. Due to higher missing data rates and fewer stations before 1961, we restricted our analysis to 1961-2015. Stations with average missing rates exceeding 1% were excluded, leaving 877 stations with less than 1% missing data annually and during spring and autumn over the 55-year period. The spatial distribution of selected stations is shown in Figure 1b [Figure 1: see original paper]. Single-day missing data were filled using the average of adjacent days, while consecutive multi-day gaps were filled via simple linear regression based on observations from the most highly correlated neighboring station without missing data during the same period.

2.3 Methods

We calculated a suite of growing season indices, including starting date (SI), ending date (EI), and length (LI), from daily mean temperature data based on different criteria (Table 1). Four indices determined the starting date and five indices determined the ending date, which were then combined into six different length indices. Since the 5°C daily mean temperature threshold is widely accepted for determining thermal growing season (Carter, 1998; Frich et al., 2002; Jones et al., 2002; Walther and Linderholm, 2006; Song et al., 2010; Dong et al., 2012; Guo et al., 2016), we employed it in all indices. Primary differences among indices lie in spell lengths when daily mean temperature exceeds 5°C (starting date) or falls below 5°C (ending date). All indices are listed in Table 1.

To evaluate inter-index relationships, we compared differences in both mean and maximum values across index combinations. Differences were first calculated year-by-year at each station. Based on the 55-year data sequence, we computed long-term averages as mean values at each station and simultaneously selected maximum values from the 55-year record. Regional mean values were calculated using station averaging, while regional maximum values were selected directly from all 877 stations, yielding one maximum value per combination.

Linear trends in time-series indices were also investigated. Using station latitude and longitude, Kriging interpolation generated spatial patterns of differences and trends for the thermal growing season, displayed via Golden Software Surfer. Given sparse station coverage in parts of northeastern China and most of western China, interpolation results in these areas may not fully reflect actual variations.

3.1.1 Starting Date of the Growing Season

Time series of mean starting dates are displayed in Figure 2 [Figure 2: see original paper]. SI 1 (=5d>5°C) showed the earliest start, while SI 4 (>5d>5°C Fr) showed the latest, with a 4.4-day difference in mean values during 1961–2015 (Table 2). SI 1 started 3.2 days earlier than SI 2 (>5d>5°C). Two frost-criterion indices (SI 3 [=5d>5°C Fr] and SI 4) had later starts than non-frost indices (SI 1 and SI 2), with differences of 1.8 and 1.2 days, respectively (Fig. 2). Thus, mean value differences between frost and non-frost indices are relatively small, with frost criterion inclusion producing smaller differences than varying spell lengths exceeding 5°C.

Across 877 stations, the largest mean value difference for starting date was 12.4 days at Wushaoling station (3045 m a.s.l.) in Gansu (Table 2). For maximum value differences, regional averages ranged from 17.5 to 28.5 days, with a maximum of 64.0 days for SI 2–SI 1 and SI 4–SI 1 pairs, both at Sheyang station in Jiangsu. Across all six index combinations, regional averaged differences were 2.2 days for mean values and 22.1 days for maximum values over 55 years. Thus, low mean differences only partially reflect value ranges, while maximum differences between indices were substantial.

3.1.2 Ending Date of the Growing Season

Among five ending indices, EI 3 (10d<5°C) showed the earliest end, while EI 2 (>5d<5°C) showed the latest, with a 9.4-day mean value difference during 1961–2015 (Table 3). EI 2 ended 1.8 days later than EI 1 (=5d<5°C), while EI 1 ended 7.6 days later than EI 3 on average. The difference between EI 4 (Fr or =5d<5°C) and EI 5 (Fr or >5d<5°C) was relatively small (1.1 days). Two frost-criterion indices (EI 5 and EI 4) had earlier ends than EI 2 and EI 1, with mean differences of 1.3 and 2.0 days, respectively (Fig. 3 [Figure 3:

see original paper]). Thus, frost criterion inclusion produced smaller differences than varying spell lengths in ending date definitions.

In northern China, the largest mean value difference for ending date was 14.1 days at Hua Shan Mountain station in Shaanxi for EI 2 vs. EI 3 during 1961–2015 (Table 3). For maximum value differences, regional averages ranged from 7.9 to 29.9 days, with a maximum of 54.0 days at Suiping station in Henan. Across all ten index combinations, regional averaged differences were 4.0 days for mean values and 23.0 days for maximum values; excluding EI 3, these became 1.6 and 20.7 days, respectively. Thus, inter-index differences were generally small for mean values, particularly when excluding EI 3, but remained large for maximum values.

3.1.3 Length of the Growing Season

Among six length indices, LI 4 (>5d>5°C Fr | 10d<5°C) showed the shortest season, while LI 1 (=5d>5°C | =5d<5°C) showed the longest, with a 12.0-day mean value difference (Table 4). LI 1 had a 9.3-day longer season than LI 3 (=5d>5°C Fr | 10d<5°C), and LI 2 (>5d>5°C | >5d<5°C) had a 10.5-day longer season than LI 4 over 55 years. The LI 1 vs. LI 2 pair showed the smallest difference (1.4 days). Two frost-criterion indices (LI 5 [=5d>5°C Fr | Fr or =5d<5°C] and LI 6 [>5d>5°C Fr | Fr or >5d<5°C]) had shorter seasons than non-frost indices (LI 1 and LI 2), with differences of 3.1 and 3.2 days, respectively (Fig. 4 [Figure 4: see original paper]). Again, frost criterion inclusion produced smaller mean value differences than varying spell lengths in season length definitions.

Across 877 stations, the largest mean value difference for season length was 22.5 days at Wushaoling station in Gansu during 1961–2015, occurring in the LI 1 vs. LI 4 pair (Table 4). For maximum value differences, regional averages ranged from 3.3 to 39.2 days, with a maximum of 93.0 days at Xifeng station (1421 m a.s.l.) in Gansu. For the entire study area, regional averaged differences were 5.7 days for mean values and 28.6 days for maximum values across all fifteen combinations. Thus, despite small average mean differences, maximum value differences were substantial.

3.2.1 Starting Date of the Growing Season

Except for several scattered stations in western China, earlier growing season onset occurred at all stations regardless of index selection. Trend differences among the four indices were relatively small, indicating minimal method-dependent effects (Fig. 5 [Figure 5: see original paper]). Starting dates advanced significantly at rates of 1.0–5.5 days per decade across southwestern, eastern, and northeastern areas, including western Qinghai, most of Inner Mongolia and

Shaanxi, north-central Heilongjiang, western Jilin, southern Liaoning, southern Hebei, Shandong, northeastern Henan, northern Anhui, northern Jiangsu, western Shanxi, Ningxia, southeastern and north-central Gansu, and parts of Xinjiang and Tibet. Areas with advances of 1.0–3.7 days per decade comprised the largest proportion.

Across all 877 stations, averaged changes in four starting indices ranged from -11.3 to -10.1 days during 1961-2015 (Table 5). Statistics showed 608, 602, 586, and 576 stations had significant advancing rates of 1.0–5.5 days per decade for SI 1, SI 2, SI 3, and SI 4, respectively—accounting for 69.3%, 68.6%, 66.8%, and 65.7% of all stations. Among these, 54.4%, 56.0%, 56.6%, and 56.3% showed significant advances of 1.0–3.0 days per decade. Areas with significant advance decreased gradually from SI 1 to SI 4 (Fig. 5). No stations showed significant later onset for any index. Frost-criterion indices produced changes averaging 1.0 day less than non-frost indices.

Over 55 years, the maximum difference in starting date changes was 19.0 days at Shangnan station in Shaanxi among four indices, while Fuping station in Hebei showed the least sensitivity to index selection. Earlier onset was less pronounced at higher altitudes (Table 5). In areas below 1000 m a.s.l., the growing season start advanced by approximately 10.6–11.5 days, while in areas between 2500–4000 m a.s.l., it advanced by only 7.7–8.6 days during 1961-2015. Tongde station (3148 m a.s.l.) in Qinghai and Huining station (1739 m a.s.l.) in Gansu showed the most remarkable advances (exceeding 27.0 days).

3.2.2 Ending Date of the Growing Season

Later growing season endings were observed across most of northern China, except for small areas in southern and western Liaoning, eastern and southern Hebei, eastern Shanxi, western and southern Henan, the northern tip of northeastern China, and two stations (Aral and Hoxud) in Xinjiang. Trend differences among five indices were small and minimally affected by index choice (Fig. 6 [Figure 6: see original paper]). Unlike the concentrated eastern and northeastern onset advances, delayed endings were significantly concentrated in western areas. In northern Tibet, most of Xinjiang and Qinghai, Jilin, central and southwestern Heilongjiang, and parts of Inner Mongolia, Gansu, Shaanxi, Shanxi, Shandong, and northern Jiangsu, ending dates delayed significantly at rates of 0.5–3.8 days per decade during 1961-2015, with 1.0–3.0 days per decade comprising the largest proportion.

Changes in ending dates were relatively small. Across five indices, averaged changes ranged from 5.1 to 5.9 days over northern China during 1961-2015 (Table 5). Stations with significant delaying rates of 0.5–3.5 days per decade numbered 297, 308, 430, 319, and 331 for EI 1, EI 2, EI 3, EI 4, and EI 5—representing 33.9%, 35.1%, 49.0%, 36.4%, and 37.7% of all stations, respectively. Among these, 31.9%, 33.5%, 46.8%, 35.0%, and 36.3% showed significant delays of 1.0–2.5 days per decade. EI 3 had the largest area with significant delay, while EI 1 had the smallest (Fig. 6). No stations showed significant earlier endings for any index. Frost-criterion indices produced changes averaging about 0.6 days more than non-frost indices.

During 1961–2015, the maximum difference in ending date changes was 25.9 days at Wushaoling station among five indices, while Nomhon station (2790 m a.s.l.) in Gansu showed the least sensitivity to index selection. Delayed endings were more pronounced at higher altitudes (Table 5). In areas below 1000 m a.s.l., ending dates delayed by approximately 4.5–5.1 days, while in areas between 2500–4000 m a.s.l., they delayed by 9.6–12.6 days over 55 years. Tongde and Wushaoling stations showed the most obvious delays (exceeding 20.0 days).

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3.2.3 Length of the Growing Season

Except for several stations in Xinjiang, Heilongjiang, and Hebei, extended growing season length occurred across the entire study area regardless of index selection, with small trend differences among six indices (Fig. 7 [Figure 7: see original paper]). Generally, season length extended significantly at rates of 0–9.1 days per decade across most of northern China during 1961–2015, with 1.5–6.0 days per decade comprising the largest proportion.

Averaged changes for six length indices ranged from 15.7 to 16.4 days during 1961–2015 (Table 5), with most stations showing extensions of 8.0–25.0 days. Stations with significant prolonging rates of 0–9.1 days per decade numbered 692, 697, 756, 749, 713, and 712 for LI 1, LI 2, LI 3, LI 4, LI 5, and LI 6—representing 78.9%, 79.5%, 86.2%, 85.4%, 81.3%, and 81.2% of all stations, respectively. Among these, 70.2%, 69.4%, 80.2%, 78.8%, 73.3%, and 71.2% showed significant prolonging rates of 1.5–4.5 days per decade. LI 3 had the largest area with significant extension, while LI 1 had the smallest. Frost-criterion indices caused season length changes averaging 0.3–0.4 days shorter than non-frost indices.

Over 55 years, the maximum difference in season length changes was 28.1 days at Wushaoling station among six indices, while Dingxin station (1177 m a.s.l.) in Gansu showed the least sensitivity to index selection. Season length prolongation was more pronounced at higher altitudes (Table 5). In areas below 1000 m a.s.l., season length extended by approximately 15.5–16.0 days, while in areas between 2500–4000 m a.s.l., it extended by 17.8–20.2 days during 1961–2015. Tongde and Wushaoling stations again showed the most prominent extensions (exceeding 40.0 days), while Aral station (1012 m a.s.l.) in Xinjiang showed small, non-significant decreases across all five indices.

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4 Discussion

Growing season length critically affects local agriculture, carbon sequestration potential, ecological environments, and human activities (Brown et al., 2010). Since mean value differences between frost and non-frost indices were relatively small, frost criterion inclusion had minimal influence on statistical analysis of growing season in northern China (Figs. 2–4). However, large maximum value differences between frost and non-frost indices indicate that frost criteria significantly affect determination of annual starting dates, ending dates, and season length at individual stations. This aligns with existing research. Walther and Linderholm (2006) noted that including or excluding frost criteria significantly impacted growing season start dates in southwestern Greater Baltic Area regions, though frost criterion exclusion during autumn was less important for ending dates. Guo et al. (2013) similarly demonstrated that frost criteria significantly influenced growing season in most central Inner Mongolia areas, particularly affecting onset timing.

During 1961-2015, northern China' s thermal growing season showed a regional average trend of 10–11 days earlier onset, 5.0–6.0 days later ending, and consequently 15.0-16.0 days prolonged length, depending on index selection (Table 5). These results align with previous studies. Song et al. (2010) reported thermal growing season extension at 2.3 days per decade in northern China during 1951–2007. Guo et al. (2014) found season length extensions of 22, 14, 17, and 15 days in desert, grassland, agricultural, and forest regions of Inner Mongolia during 1961–2010. Shen et al. (2012) observed 8.4 days earlier onset and 5.7 days later ending in temperate China from 1960–2009. Guo et al. (2016) reported 9.0–11.1 days earlier tree growing season onset and 4.8–5.8 days later ending, extending season length by 13.3 days in Hebei-Shanxi mountainous regions and 16.4 days in the Loess Plateau from 1961-2013.

In northern China, different indices from the same category had relatively small impacts on long-term growing season trends, though some regional differences existed and were not homogeneous across the entire area (Figs. 5–7). Walther and Linderholm (2006) compared numerous growing season definitions in the Greater Baltic Area and also found trend differences in season length depending on definition used. Additionally, the 877 meteorological stations were unevenly distributed, with most concentrated in southeastern northern China (Fig. 1). Station distribution was sparse in southwestern areas including southern Xinjiang, northern Tibet, and southwestern Qinghai. Given that deserts, mountains, and bare lands dominate these regions, we calculated mean and maximum values using station data; the relatively limited station numbers had minimal impact on results, though interpolation uncertainties may exist.

Thermal growing season can only approximate the real growing season to a certain extent and should be viewed as a modeling approach using daily mean temperature (Walther and Linderholm, 2006). Ground observation phenological data provide actual growing season parameters because they integrate all environmental factors promoting plant growth in specific areas. Zheng et al. (2002) analyzed plant phenology changes across China using data from 26 stations, finding advanced spring phenophases in northern and northeastern China and the lower Yangtze region, but delayed phenophases in the middle Yangtze reaches and eastern southwestern China since the 1980s. Hao et al. (2017) analyzed ligneous plant phenology in Kashgar Prefecture, showing spring phenology advanced gradually by 8 days during 1985-2012. Yang et al. (2016) found that Larix gmelinii growing season prolonged in the Greater Khingan Mountains, with first leaf unfolding and leaf fall end delayed by 17.3 and 12.1 days per decade, respectively, during 1987-2012. However, phenological data availability remains limited and covers shorter time scales.

Satellite remote sensing data now provide continuous coverage and fine spatial resolution for regional or global vegetation monitoring, becoming widely used in phenology studies (White et al., 2005; Wang et al., 2016). For example, Høgda et al. (2013) analyzed growing season trends in Fennoscandia using Global Inventory Modeling and Mapping Studies NDVI3g data, revealing 9.8-13.8 days earlier onset during 1982-2011. Nagai et al. (2015) examined growing season timing variations in Japan using daily satellite-observed green-red vegetation index, finding ending date sensitivity to air temperature was much lower than starting date sensitivity in deciduous broadleaf and needle-leaf forests during 2003-2012. Chi et al. (2016) demonstrated heterogeneous growing season onset trends for different vegetation types in Xilin Gol League, China, using 1-km resolution NOAA/AVHRR NDVI data during 1989-2009. Wang et al. (2016) investigated growing season onset, length, and ending in the Loess Plateau using NDVI data, showing 54.84% of vegetation had earlier onset while 67.64% had later ending during 2000-2010. Future research should focus on careful index selection and applicability comparison across diverse temperature thresholds, integrating satellite remote sensing monitoring with plant phenological observations.

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5 Conclusions

In northern China, maximum value differences among thermal growing season parameters (starting date, ending date, and length) were large, though mean value differences between indices were small. Therefore, careful index selection and applicability comparison across diverse geographic and climatic regions are necessary. Frost criterion inclusion caused minimal mean value differences—smaller than those from varying spell lengths—but produced large maximum value differences between frost and non-frost indices. Thus, frost criterion consideration is important for determining annual growing season timing and length in northern China.

Over the past 55 years, regional average trends showed 10-11 days earlier onset, 5.0-6.0 days later ending, and consequently 15.0-16.0 days prolonged thermal growing season length in northern China. Spatially, starting dates advanced significantly at 1.0-3.7 days per decade in southwestern, eastern, and northeastern regions; ending dates delayed significantly at 1.0-3.0 days per decade in western areas; and season length prolonged significantly at 1.5-6.0 days per decade across most of northern China. With increasing altitude, the advancing rate of season onset decreased while the delaying rate of season ending increased rapidly, correspondingly increasing the prolongation rate of season length.

Acknowledgements: This work was supported by the National Natural Science Foundation of China (41571044, 41401661, 41001283), the Climate Change Special Fund of the China Meteorological Administration (CCSF201716), and the China Clean Development Mechanism (CDM) Fund Project (2012043).

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Note: Figure translations are in progress. See original paper for figures.