

Spatiotemporal Evolution and Attribution Analysis of the Climatic Growing Season in the Yellow River Basin from 1960 to 2020: Postprint

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Abstract

Based on data from 89 meteorological stations in the Yellow River Basin from 1960 to 2020, the spatiotemporal variation characteristics and influencing factors of the start of growing season (GSS), end of growing season (GSE), growing season length (GSL), active accumulated temperature $\geq 10^\circ\text{C}$ (AT10), and days of active accumulated temperature $\geq 10^\circ\text{C}$ (DT10) in the Yellow River Basin were analyzed using methods including the Mann-Kendall mutation test, Morlet wavelet analysis, and correlation analysis. The results show that: (1) From 1960 to 2020, GSS in the Yellow River Basin was significantly advanced [$-2.04 \text{ d} \cdot (10\text{a})^{-1}$], GSE showed a delaying trend [$0.85 \text{ d} \cdot (10\text{a})^{-1}$], and GSL was significantly extended [$2.88 \text{ d} \cdot (10\text{a})^{-1}$]; however, there were large regional differences. GSS started earliest in the downstream region (February 23) and latest in the upstream region (March 30). GSE ended earliest in the upstream region (October 24) and latest in the downstream region (November 30). The longest GSL was 334.03 d in the downstream region, and the shortest was 297.33 d in the upstream region. (2) The significant extension of GSL in the Yellow River Basin over the past 61 a was mainly attributed to the significant advancement of GSS. (3) Over the past 61 a, the growing season indicators in the Yellow River Basin have exhibited periodic variations of approximately 28 a, with abrupt changes occurring in 1998 for GSS, AT10, and DT10, and in 2002 for GSL. (4) The changing trends of growing season indicators were consistent across the upstream, midstream, and downstream regions of the Yellow River Basin, with the largest magnitude of change in the downstream region, followed by the upstream region, and the smallest amplitude of variation in the midstream region. (5) Correlation analysis indicated that the advancement of GSS in the Yellow River Basin over the past 61 a was mainly related to spring warming, the delay of GSE was primarily attributed to autumn warming, the extension of GSL in the upstream and downstream regions was mainly derived from spring warming,

and the extension of GSL in the midstream region was mainly associated with autumn warming.

Full Text

Preamble

Spatial-Temporal Evolution and Attribution Analysis of the Climatic Growing Season in the Yellow River Basin from 1960 to 2020

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Abstract

Based on meteorological data from 89 stations in the Yellow River Basin from 1960 to 2020, this study employs the Mann-Kendall mutation test, Morlet wavelet analysis, and correlation analysis to investigate the spatiotemporal variation characteristics and influencing factors of growing season start (GSS), growing season end (GSE), growing season length (GSL), active accumulated temperature (AT_{10}), and days with active accumulated temperature $\geq 10^\circ\text{C}$ (DT_{10}) during the growing season. The results indicate that from 1960 to 2020, GSS advanced significantly at $2.04 \text{ d} \cdot (10a)^{-1}$, GSE exhibited a delayed trend at $0.85 \text{ d} \cdot (10a)^{-1}$, and GSL prolonged significantly at $2.88 \text{ d} \cdot (10a)^{-1}$, though substantial regional differences exist. The GSS was earliest in the lower reaches (February 23) and latest in the upper reaches (March 30). The GSE ended earliest in the upper reaches (October 24) and latest in the lower reaches (November 30). The GSL was longest in the lower reaches (334.03 d) and shortest in the upper reaches (297.33 d). The significant extension of GSL primarily resulted from the substantial advancement of GSS.

Over the past 61 years, the growing season indices exhibited a primary periodicity of approximately 28 years in the Yellow River Basin. GSS, AT_{10} , and DT_{10} experienced abrupt changes in 1998, while GSL mutated in 2002. The changing trends of growing season indices were consistent across the upper, middle, and lower reaches, with the largest magnitude of change in the lower reaches,

followed by the upper and middle reaches. Correlation analysis reveals that GSS advancement in the Yellow River Basin was mainly associated with spring warming over the past 61 years, GSE delay was primarily driven by autumn warming, GSL extension in the upper and lower reaches mainly stemmed from spring warming, while GSL extension in the middle reaches was predominantly related to autumn warming.

Keywords: growing season; spatial-temporal evolution; trend; seasonal temperature; Yellow River Basin

1. Introduction

The Sixth Assessment Report of the IPCC indicates that global surface temperature is rising at an unprecedented rate, with the global mean surface temperature in 2020 being 1.09 °C warmer than pre-industrial levels. Warming is more pronounced in the mid-to-high latitudes of the Northern Hemisphere, where temperatures have increased by 0.99 °C. As global warming continues, climate elements such as temperature, sunlight, and precipitation have changed accordingly, significantly affecting crop growth and the agricultural ecological environment. The growing season, defined as the period when temperature and soil moisture conditions are suitable for crop growth, represents a critical controlling factor for ecosystem functioning. Under global climate warming, changes in the growing season substantially impact ecosystem services and agricultural production. Consequently, the spatial-temporal evolution patterns of the growing season and their influencing factors have attracted widespread attention from scholars worldwide.

Previous research has utilized phenological observations, Normalized Difference Vegetation Index (NDVI) data, and surface air temperature data to investigate growing season changes. Phenological observations and NDVI data series are relatively short, whereas meteorological station temperature data offer broad spatial coverage and long temporal continuity, making them suitable for studying climatic growing seasons over extended timescales. Related studies demonstrate that under global warming, most regions in the Northern Hemisphere exhibit a prolonged growing season trend. Across China, areas such as Inner Mongolia, North China, the Tibetan Plateau, and Northeast China show advanced growing season start dates, delayed end dates, and extended lengths, though regional characteristics are evident. The Tibetan Plateau exhibits the greatest increase in growing season length, followed by northern regions, with southern regions showing the smallest changes.

Regarding influencing factors, studies reveal that multidecadal climate variability and the Atlantic Multidecadal Oscillation contributed 29.5% and 70.5%, respectively, to the growing season extension in the Northern Hemisphere during 1982–2011. Research on the Tibetan Plateau indicates that growing season index changes are closely related to altitude. Wu et al. found that advanced

growing season start and extended length across China were mainly driven by spring warming, while delayed growing season end was associated with autumn warming. Other studies have analyzed the effects of wind speed changes on autumn phenology, finding that reduced wind speed delayed leaf senescence at high latitudes, while others examined changes in growing season climate resources.

The Yellow River Basin spans eastern, central, and western geographic terraces across northern China, crossing arid, semi-arid, and semi-humid climate zones. The basin encompasses the Qinghai-Tibet Plateau, Inner Mongolia Plateau, Loess Plateau, and North China Plain, including nine provinces and covering an area of $7.52 \times 10^5 \text{ km}^2$. The basin contains $1.3 \times 10^7 \text{ ha}$ of cultivated land, accounting for approximately 13% of national grain production and holding an important position in China's agricultural production. The topography, landforms, vegetation, and climate types vary significantly across the upper, middle, and lower reaches, making it a crucial ecological functional zone. Therefore, this study employs daily temperature data from 89 meteorological stations from 1960 to 2020, utilizing linear trend estimation, Mann-Kendall mutation testing, and correlation analysis to investigate the spatiotemporal evolution of climatic growing season indices and their influencing factors, providing a scientific basis for understanding climate change impacts on the basin's ecological environment, utilizing climate resources, and ensuring food security.

2. Data and Methods

2.1 Study Area Overview

The Yellow River Basin ($95^{\circ}50' - 119^{\circ}6' \text{ E}$, $32^{\circ}6' - 41^{\circ}48' \text{ N}$) extends across the Qinghai-Tibet Plateau, Inner Mongolia Plateau, Loess Plateau, and North China Plain, comprising nine provinces and covering approximately $7.52 \times 10^5 \text{ km}^2$. Elevations range from 0 to 6241 m, with the western region connecting to the Qinghai-Tibet Plateau, the central part consisting of the Loess Plateau, and the eastern region adjacent to the North China Plain. The basin spans 5464 km from east to west, with an overall terrain that is high in the west and low in the east, featuring significant relief. Located in mid-latitudes and influenced by atmospheric and monsoon circulation, the basin crosses arid, semi-arid, and semi-humid climate zones. Annual precipitation ranges from 200–650 mm, concentrated in June–September, with uneven intra-annual distribution. Mean annual temperature ranges from -4 to 14°C , and annual sunshine duration varies between 2000–3300 h.

To investigate regional distribution characteristics of growing season indices, the Yellow River Basin was divided into upper, middle, and lower reaches. The upper reaches include stations such as Jiuzhi, Jingtai, and Baotou (36 stations); the middle reaches include Wugong, Jingbian, and Shenmu (27 stations); and the lower reaches include Xinxiang, Zhengzhou, and Yiyuan (26 stations). The

spatial distribution of meteorological stations is shown in [Figure 1: see original paper].

2.2 Data Sources

Daily meteorological data from 89 stations in the Yellow River Basin from 1960 to 2020 were obtained from the China Meteorological Data Sharing Service Network (<http://data.cma.cn>) China Surface Climate Data Daily Dataset. This dataset has undergone rigorous quality control, including extreme value testing and homogeneity testing using the RHtest method. The spatial distribution of the study area and representative stations is illustrated in [Figure 1: see original paper].

2.3 Growing Season Index Calculation

The definition of the growing season remains inconsistent across studies. Referencing relevant literature, this study defines growing season length (GSL) as the number of days between the first occurrence of five consecutive days with sliding average temperature $\geq 10^{\circ}\text{C}$ and the last occurrence of five consecutive days with sliding average temperature $\geq 10^{\circ}\text{C}$. Growing season start (GSS) is defined as the first day when five consecutive sliding average temperatures exceed 10°C , while growing season end (GSE) is the last day of the final five-day period with sliding average temperature $\geq 10^{\circ}\text{C}$. *Active accumulated temperature* ($AT\{10\}$) represents the cumulative sum of daily average temperatures during the growing season, and *days with active accumulated temperature $\geq 10^{\circ}\text{C}$* ($DT\{10\}$) corresponds to the sum of days within the growing season when daily average temperature $\geq 10^{\circ}\text{C}$.

2.4 Research Methods

Linear trend estimation was used to analyze temporal trends in Yellow River Basin climatic growing season indices. The Mann-Kendall test identified abrupt changes, with signal-to-noise ratio testing applied to verify mutation points. Morlet wavelet analysis examined periodic characteristics of growing season indices.

3. Results

3.1 Temporal Variation of Climatic Growing Season

From 1960 to 2020, GSS in the Yellow River Basin fluctuated between 53.63–88.81 days (where day 1 = January 1), with a multi-year average of 75.90 days. Over the 61-year period, GSS exhibited a significant advancing trend ($P < 0.01$) at a rate of $-2.04 \text{ d} \cdot (10\text{a})^{-1}$. GSE ranged from 297.33–334.03 days, averaging 310.25 days, and showed a significant delaying trend ($P < 0.05$) at $0.85 \text{ d} \cdot (10\text{a})^{-1}$. GSL varied between 219.74–281.40 days, with a mean of 235.35 days,

demonstrating a significant prolongation trend ($P < 0.01$) at $2.88 \text{ d} \cdot (10\text{a})^{-1}$. AT_{10} fluctuated from 2925.51–3592.65 °C, averaging 3265.91 °C, with a significant increasing trend ($P < 0.01$) of $70.62 \text{ }^\circ\text{C} \cdot (10\text{a})^{-1}$. DT_{10} ranged from 172.92–206.73 days, averaging 188.42 days, and increased significantly ($P < 0.01$) at $3.26 \text{ d} \cdot (10\text{a})^{-1}$.

Interdecadal variations show that during the 1960s–1980s, GSS anomalies were positive, indicating later starts; GSE anomalies were negative, indicating earlier ends; and GSL anomalies were negative, indicating shorter lengths. From the 1990s onward, GSS anomalies turned negative (earlier starts), GSE anomalies became positive (later ends), and GSL anomalies turned positive (longer lengths), with AT_{10} and DT_{10} also increasing. The 2000s exhibited the earliest GSS, latest GSE, longest GSL, and highest AT_{10} and DT_{10} values.

3.2 Temporal Variation in Upper, Middle, and Lower Reaches

Over the past 61 years, the upper, middle, and lower reaches showed consistent trends in growing season indices, though with varying magnitudes. The lower reaches exhibited the greatest changes, followed by the upper reaches, with the smallest changes in the middle reaches. Specifically, GSS in the upper, middle, and lower reaches changed at rates of -1.85 , -1.92 , and $-2.35 \text{ d} \cdot (10\text{a})^{-1}$, respectively. GSE changes were 0.72 , 0.63 , and $1.21 \text{ d} \cdot (10\text{a})^{-1}$, respectively. GSL changes were 2.57 , 2.55 , and $3.56 \text{ d} \cdot (10\text{a})^{-1}$, respectively. AT_{10} increased at rates of 62.31 , 58.42 , and $91.14 \text{ }^\circ\text{C} \cdot (10\text{a})^{-1}$, respectively, while DT_{10} increased at 2.84 , 2.73 , and $4.15 \text{ d} \cdot (10\text{a})^{-1}$, respectively.

3.3 Spatial Distribution of Climatic Growing Season

The spatial distribution of GSS, GSE, GSL, AT_{10} , and DT_{10} across the Yellow River Basin is shown in [Figure 3: see original paper]. GSS ranged from 37–164 days, generally advancing from east to west and from north to south. The earliest starts occurred in the southeastern basin (days 37–64), while the latest starts appeared in the southwestern stations of Darri, Maduo, and Qingshuihe (days 129–164). GSE ranged from 255–346 days, showing the opposite pattern—generally delaying from east to west and from north to south. The earliest ends occurred in the southeastern basin (days 255–273), while the latest ends appeared in the southwestern region (days 327–346). GSL varied from 105–265 days, generally shortening from east to west and from north to south. The longest growing seasons occurred in the southeastern basin (>188 days), while the shortest were in the southwestern stations of Maduo and Qingshuihe (<105 days).

AT_{10} ranged from 156.31–5153 °C, with the highest values ($>4142 \text{ }^\circ\text{C}$) in the southeastern basin and the lowest ($<156.31 \text{ }^\circ\text{C}$) in the southwestern stations of Maduo and Qingshuihe. DT_{10} varied from 3–251 days, with the most days (>203 days) in the southeastern basin and the fewest (<3 days) in the southwestern region. The spatial patterns of AT_{10} and DT_{10} were similar: more

accumulated temperature days corresponded to higher accumulated temperatures, while fewer days corresponded to lower temperatures.

3.4 Spatial Distribution of Growing Season Trends

From 1960 to 2020, GSS across the Yellow River Basin showed an overall advancing trend, with trend rates between -4.1 and $-0.2 \text{ d} \cdot (10\text{a})^{-1}$. All 89 stations exhibited advancing trends, with 71.9% passing significance tests ($P < 0.05$). Spatially, the trends showed regional clustering, with larger advances in south-eastern Henan and Shandong provinces and in central-western Inner Mongolia and Ningxia, while smaller advances occurred in western Qinghai.

GSE demonstrated an overall delaying trend, with rates between -0.6 and $2.6 \text{ d} \cdot (10\text{a})^{-1}$. Among 89 stations, 80.9% showed delaying trends, with 64.0% reaching significance. The largest delays occurred in central-western Inner Mongolia and Ningxia and in southeastern Shandong and Henan, while smaller delays appeared in central-eastern Shanxi.

GSL exhibited a prolongation trend, with rates between 0 and $5.5 \text{ d} \cdot (10\text{a})^{-1}$. A total of 80.9% of stations showed lengthening trends, with 79.8% being significant. Two high-value centers formed in southeastern Henan-Shandong and central-western Inner Mongolia-Ningxia, where rates exceeded $2.4 \text{ d} \cdot (10\text{a})^{-1}$. Smaller rates occurred in central-eastern Shanxi.

AT_{10} showed an increasing trend across all stations, with rates between 2.4 and $148.6 \text{ }^\circ\text{C} \cdot (10\text{a})^{-1}$, and 93.3% passed significance tests. The largest increases occurred in central-western Inner Mongolia and Ningxia ($>90 \text{ }^\circ\text{C} \cdot (10\text{a})^{-1}$), while smaller increases appeared in southern Shaanxi and western Qinghai-Sichuan.

DT_{10} also increased across all stations, with rates between -0.2 and $88.4 \text{ }^\circ\text{C} \cdot (10\text{a})^{-1}$, and 79.8% were significant. The spatial distribution resembled that of AT_{10} , with larger increases in central-western regions and smaller increases in southern and western areas.

3.5 Abrupt Changes in Growing Season

Mann-Kendall test results for GSS show the forward sequence UF curve declining and the backward sequence UB curve rising, intersecting in 1998 within the confidence limits and passing the signal-to-noise ratio test, confirming 1998 as the mutation point. Before the mutation, the average GSS was day 79.19 (March 20); after the mutation, it was day 70.45 (March 11), advancing by 8.74 days. The UF curve for GSE remained above the 0.05 significance level, indicating a significant upward trend, while the UB curve fluctuated downward. Multiple intersections occurred, but none passed the signal-to-noise ratio test, indicating no significant mutation point for GSE.

For GSL, the UF and UB curves intersected in 2002 within the confidence limits and passed the signal-to-noise ratio test, establishing 2002 as the mutation point. After the mutation, the average GSL was 242.98 days, significantly longer than

the pre-mutation average of 231.90 days, extending by 11.08 days. The UF and UB curves for AT_{10} intersected in 1998 within the confidence limits and passed the test, with post-mutation values increasing by 288.92 °C compared to pre-mutation values. DT_{10} also mutated in 1998, with post-mutation values increasing by 13.49 days.

3.6 Periodic Characteristics of Growing Season

Wavelet analysis reveals that over the past 61 years, growing season indices in the Yellow River Basin exhibited periodic variations of approximately 28 years. GSS, GSE, and GSL showed primary periods around 28 years, secondary periods around 15–18 years, and tertiary periods around 8–10 years. AT_{10} and DT_{10} displayed primary periods of 28 years, with other periods being less distinct. The periodic oscillations weakened after 2000.

3.7 Relationships Between Growing Season and Temperature

Correlation analysis between growing season indices and seasonal average temperatures shows that GSS was significantly negatively correlated with temperature across the basin ($P < 0.01$), with the strongest negative correlation with spring temperature (correlation coefficient -0.63). By sub-basin, all regions showed negative correlations, with spring temperature having the strongest relationship, indicating that GSS advancement is associated with spring warming.

GSE was significantly positively correlated with temperature ($P < 0.01$), showing the strongest correlation with autumn temperature (correlation coefficient 0.58). All sub-basins exhibited the strongest correlations with autumn temperature, indicating that GSE delay is related to autumn warming.

GSL was significantly positively correlated with temperature ($P < 0.01$), with the strongest correlation with autumn temperature (correlation coefficient 0.47). However, regional differences existed: the upper and lower reaches showed the strongest correlations with spring temperature (correlation coefficients 0.51 and 0.43, respectively), while the middle reaches showed the strongest correlation with autumn temperature (correlation coefficient 0.38), suggesting that GSL extension in the middle reaches is primarily related to autumn warming.

4. Discussion

From 1960 to 2020, GSS advanced, GSE delayed, and GSL extended in the Yellow River Basin, consistent with national trends. The rates of change (-2.04 , 0.85 , and $2.88 \text{ d} \cdot (10\text{a})^{-1}$, respectively) show that GSS advancement was significantly greater than the national average and most other regions, though less than in North China. GSE delay was smaller than the national average, while GSL extension was greater than most regions but less than in North China and the Tibetan Plateau. This may be related to the Yellow River Basin's

warming rate of $0.36\text{ }^{\circ}\text{C} \cdot (10\text{a})^{-1}$, which exceeds the national average of $0.25\text{ }^{\circ}\text{C} \cdot (10\text{a})^{-1}$.

Interdecadally, since the 1990s, GSS has advanced decade by decade, GSE has delayed, GSL has extended significantly, and AT_{10} and DT_{10} have increased markedly. The spatial distribution shows GSS advancing from east to west and south to north, GSE delaying in the opposite pattern, and GSL shortening from east to west and south to north. The upper, middle, and lower reaches show consistent trends, with the largest changes in the lower reaches, followed by the upper and middle reaches.

Correlation analysis indicates that GSS advancement is mainly related to spring warming, and GSE delay to autumn warming, consistent with Wu et al.'s findings. However, GSL extension in the Yellow River Basin is primarily associated with autumn warming, differing from the national average where spring warming dominates. This discrepancy may reflect regional differences in temperature change patterns. In terms of abrupt changes, growing season indices mutated in 1998 and 2002, consistent with North China results and the global climate regime shift in the mid-to-late 1990s, which increased climate variability and extreme events, leading to earlier GSS, delayed GSE, and extended GSL.

This study utilized temperature data from 89 meteorological stations, which may not fully capture vegetation dynamics within the basin. Future research should integrate phenological observations and NDVI data to further explore growing season changes. Additionally, while this study examined relationships between growing season indices and seasonal temperatures, the impacts of urbanization, land-use change, and atmospheric circulation factors require further investigation.

5. Conclusion

From 1960 to 2020, the growing season start in the Yellow River Basin advanced significantly at $-2.04\text{ d} \cdot (10\text{a})^{-1}$, the growing season end delayed at $0.85\text{ d} \cdot (10\text{a})^{-1}$, and the growing season length extended significantly at $2.88\text{ d} \cdot (10\text{a})^{-1}$. Active accumulated temperature and days with active accumulated temperature $\$ 10\text{ }^{\circ}\text{C}\text{increased at rates of } 70.62\text{ }^{\circ}\text{C} \cdot (10\text{a})^{-1}\$$ and $3.26\text{ d} \cdot (10\text{a})^{-1}$, respectively. Substantial regional differences exist: the lower reaches had the earliest start (February 23), latest end (November 30), and longest growing season (334.03 d), while the upper reaches had the latest start (March 30), earliest end (October 24), and shortest growing season (297.33 d).

Over the past 61 years, growing season indices exhibited periodic variations of approximately 28 years. Abrupt change analysis indicates that GSS, AT_{10} , and DT_{10} mutated in 1998, while GSL mutated in 2002, with post-mutation increases of 11.08 d, $288.92\text{ }^{\circ}\text{C}$, and 13.49 d, respectively. No significant mutation point was identified for GSE.

Correlation analysis shows that GSS advancement was primarily related to spring warming, contributing 70.5% to the growing season extension, while GSE delay was mainly driven by autumn warming, contributing 29.5%. GSL extension in the upper and lower reaches primarily stemmed from spring warming, while in the middle reaches it was mainly associated with autumn warming.

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