Spatiotemporal Variations of $ $0 ℃ and $ $10 ℃ Accumulated Temperature on the Loess Plateau Under Climate Warming (Postprint)

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Abstract

The Loess Plateau is a climate-change-sensitive region in China, and studying the spatiotemporal variation characteristics of its accumulated temperature is conducive to comprehensively understanding the thermal resource status of the Loess Plateau against the backdrop of climate warming. Based on daily mean temperature data from 55 meteorological stations on the Loess Plateau from 1960 to 2019, and using research methods such as linear fitting, abrupt change detection, and dominance analysis, this study analyzed the spatiotemporal variation characteristics of the start date, end date, duration, and active accumulated temperature for $ $0 ℃ and $ $10 ℃ accumulated temperatures on the Loess Plateau. The results show: (1) From 1960 to 2019, the various indicators of $ $0 ℃ and $ $10 ℃ accumulated temperatures on the Loess Plateau exhibited synchrony, all showing trends of earlier start dates, later end dates, extended duration, and increased active accumulated temperature (P<0.01); most indicators underwent a shift from the late 1990s to the early 2000s; the spatial distribution of mean values for the indicators of both types of accumulated temperature showed consistency, both exhibiting gradually earlier start dates (later end dates/extended duration/increased active accumulated temperature) from northwest to southeast; the spatial variation in trend changes among the indicators was significant. (2) Changes in the start date, end date, and duration of $ $0 ℃ accumulated temperature on the Loess Plateau were mainly jointly influenced by latitude and elevation, while changes in other indicators of accumulated temperature were primarily affected by elevation; the contribution rates of start date changes to duration changes for $ $0 ℃ and $ $10 ℃ accumulated temperatures were 65.1% and 68.4%, respectively. (3) Compared with 1960–1989, the trend changes of most indicators for $ $0 ℃ and $ $10 ℃ accumulated temperatures remained unchanged during 1990–2019; the contribution rates of start date changes to duration changes decreased by 2.3% and increased by 15.2%, respectively, showing an alternating distribution of "high-low-high" from south to west, and higher in the southeast and lower in the northwest, respectively. The start date, end date, duration, and active accumulated temperature of $ $0 ℃ and $ $10 ℃ accumulated temperatures on the Loess Plateau respond significantly to climate warming, and their variation characteristics exhibit obvious regional and phased nature.

Full Text

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Abstract: The Loess Plateau is a climate-sensitive region in China, and studying the spatio-temporal variation characteristics of its accumulated temperature is crucial for comprehensively understanding temperature resource conditions under climate warming. Based on daily average temperature data from meteorological stations on the Loess Plateau from 1960 to 2019, this study analyzed the spatio-temporal variation characteristics of $ $10°C accumulated temperature using linear fitting, mutation tests, and dominance analysis. The results show that the various indicators of accumulated temperature exhibited synchronous changes, all showing trends of earlier first date, later ending date, longer duration, and increased active accumulated temperature ($P<0.01$). Most indicators underwent interdecadal shifts in the 1990s, with abrupt changes concentrated between the late 1990s and early 2000s. The spatial distribution of multi-year average values showed consistent patterns, with first dates advancing, ending dates delaying, duration extending, and active accumulated temperature increasing from northwest to southeast. However, the spatial patterns of trend magnitudes varied significantly: the advance of first dates showed a "high-low-high" alternating pattern along the southeast-northwest direction; the delay of ending dates showed a "high-low" alternating distribution along the east-west direction; the increase in active accumulated temperature showed an east-high-west-low pattern; and the extension of duration showed a west-high-east-low pattern. Changes in first date, ending date, and duration for $ $10°C accumulated temperature were jointly influenced by latitude and altitude, while other indicators were primarily affected by altitude, with contribution rates ranging from 65.59% to 72.17%. The contribution rates of first date changes to duration changes were 65.1% for $ $10°C and 68.4% for $ $0°C, showing a decreasing trend from east to west. Compared with the period before 1990, most indicators showed unchanged trend directions, but the magnitude of change became more pronounced.

Keywords: active accumulated temperature; dominance analysis; contribution rate; spatio-temporal variation; Loess Plateau

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1 Data and Methods

The daily average temperature data used in this study were obtained from the China Ground Climate Data Daily Value Dataset (V3.0), which has undergone quality control checks including station extreme values, climate boundary values, and internal consistency, ensuring data reliability. Based on principles of less than 10% missing data within a year and longest observation periods, we established average temperature series for 55 representative meteorological stations on the Loess Plateau (Fig. 1). Following the research of Liu et al. [31], the Loess Plateau was divided into three ecological sub-regions: the East Asian Monsoon Ecological Sub-region, the Northwest Arid Ecological Sub-region, and the Qinghai-Tibet Plateau Ecological Sub-region, containing 29, 17, and 9 meteorological stations respectively.

The accumulated temperature indicators studied include: first date (FD), ending date (ED), duration days (DD), and active accumulated temperature (AIT). The calculation principles for these indicators are detailed in reference [8]. To facilitate comparison of spatio-temporal variation characteristics [9], the study period was divided into two sub-periods: 1960-1989 and 1990-2019.

Linear fitting was used to calculate trends for each accumulated temperature indicator on the Loess Plateau, with significance testing at three levels: non-significant ($P>0.05$), significant ($P<0.05$), and highly significant ($P<0.01$). The Mann-Kendall mutation test [10] and moving T-test were employed to identify abrupt changes in various accumulated temperature indicators. Dominance analysis [11] was used to determine the main geographical factors affecting $ $10°C accumulated temperature indicators and to calculate the contribution rates of first date and ending date changes to duration changes. The calculation principles are detailed in reference [11]. Origin 2021 and ArcGIS 10.8 were used to produce temporal variation charts and spatial distribution maps for each accumulated temperature indicator.

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2 Results and Analysis

2.1 Temporal Variation Characteristics of $ $10°C Accumulated Temperature Indicators

2.1.1 Interannual Variation Overall, from 1960 to 2019, the average temperature on the Loess Plateau showed a fluctuating upward trend at a rate of $0.031°C \cdot a^{-1}$ (P<0.01), higher than the national warming rate of $0.022°C \cdot a^{-1}$. Against this warming background, the first dates of both $ $0°C and $ $10°C accumulated temperature showed highly significant advancing trends at rates of $0.186d \cdot a^{-1}$ and $0.158d \cdot a^{-1}$ respectively (P<0.01), fluctuating between early March and late April (early April to late May). The ending dates showed delaying trends at rates of $0.130d \cdot a^{-1}$ and $0.128d \cdot a^{-1}$ respectively (P<0.01), varying between late October and early December (late September to mid-November). Influenced by the combined effect of earlier first dates and later ending dates, the duration days of both accumulated temperature thresholds showed extending trends at rates of $0.288d \cdot a^{-1}$ and $0.314d \cdot a^{-1}$ respectively (P<0.01). Active accumulated temperature also showed highly significant increasing trends of $7.50°C \cdot d \cdot a^{-1}$ and $7.55°C \cdot d \cdot a^{-1}$ respectively (P<0.01).

Compared with the period 1960-1989, all indicators except the first date of $ $10°C accumulated temperature showed varying degrees of advancement (delay), extension (increase) during 1990-2019, with the $ $10°C indicators showing more pronounced changes.

2.1.2 Interdecadal Variation From an interdecadal perspective (Table 1), the first date of $ $10°C accumulated temperature was later than average in the 1960s-1980s, then became earlier after the 1990s, with the most significant advancement in the 2000s (-4.85 d) and a slight delay in the 2010s (2.68 d). The ending date was earlier in the 1960s-1970s, later in the 1980s-1990s, and showed the most significant delay in the 2000s (4.39 d). The interdecadal variation patterns of duration days and active accumulated temperature were basically consistent with those of the ending date, both showing the highest positive anomalies in the 2000s. For $ $0°C accumulated temperature, the interdecadal variation patterns were similar to those of $ $10°C, but the transitions between positive and negative anomalies lagged by one decade compared to $ $10°C.

Further calculations revealed that the interval days between the first dates of $ $0°C and $ $10°C accumulated temperature decreased at a rate of $0.028d \cdot a^{-1}$ from 43.43 d in the 1960s to 42.16 d in the 2010s, while the interval days between ending dates remained stable at 46.79 d with no significant change. This indicates that the advancement of the first date was more pronounced than the delay of the ending date, and the advancement of $ $10°C first date was more significant than that of $ $0°C.

2.1.3 Abrupt Change Characteristics During 1960-2019, all accumulated temperature indicators on the Loess Plateau underwent significant abrupt changes, concentrated between the late 1990s and early 2000s (Table 2), slightly later than the average temperature mutation time (1993) [12], suggesting a lag effect of temperature on accumulated temperature and phenology [13]. Compared with pre-mutation periods, post-mutation periods showed: first dates advanced by 5.89 d and 6.75 d; ending dates delayed by 6.29 d and 5.06 d; duration days extended by 12.96 d and 11.12 d; and active accumulated temperature increased by $321.08°C \cdot d$ and $296.39°C \cdot d$ for $ $0°C and $ $10°C respectively. The first date mutation occurred earlier than the ending date for $ $0°C, while the opposite was true for $ $10°C. The mutation times for duration days and active accumulated temperature were the earliest, occurring in 1997 and 1998 respectively.

2.2 Spatial Variation Characteristics of $ $10°C Accumulated Temperature Indicators

2.2.1 Spatial Variation of First Date, Ending Date, and Duration Days

Overall, the multi-year average first dates of $ $0°C and $ $10°C accumulated temperature on the Loess Plateau showed a spatial pattern of gradually advancing from northwest to southeast. The earliest first dates were at Wugong Station in the Fenwei Plain (March 7) and Yuncheng Station in Shanxi (April 8), while the latest were at Huajialing Station in the cold highland of central Gansu (April 17 and May 13 respectively). The earliest and latest ending dates were also at Huajialing Station (October 25 and September 18) and Sanmenxia Station (December 5 and November 2), showing a south-north spatial pattern of longer duration in the south and shorter in the north. Huajialing Station had the shortest duration (216 d and 98.28 d), while Sanmenxia Station had the longest (312.07 d and 211.45 d).

Most areas of the Loess Plateau showed advancing trends in first dates, with 98.28% of stations reaching significant levels (P<0.05). The advancement magnitude showed a "high-low-high" alternating pattern along the southeast-northwest direction, with the greatest advancement at Linfen Station (-0.338 $d \cdot a^{-1}$) and Yuncheng Station (-0.319 $d \cdot a^{-1}$). The advancement magnitude exhibited a pattern of higher values in central regions and lower in peripheral areas, particularly high around Yulin and Yuncheng stations.

All stations showed delaying trends in ending dates, with the delay magnitude following an east-west "high-low-high" alternating distribution. The most significant delays were concentrated west of the Liupan Mountains and east of the Fen River, particularly at Tongren Station (0.262 $d \cdot a^{-1}$) and Yuanping Station (0.320 $d \cdot a^{-1}$). Duration days at all stations showed extending trends, with 94.5% of stations reaching highly significant levels (P<0.01). The extension magnitude showed a west-high-east-low spatial pattern, with the most significant extension at Tongren Station (0.601 $d \cdot a^{-1}$), consistent with the findings of He et al. [14].

2.2.2 Spatial Variation of Active Accumulated Temperature The multi-year average active accumulated temperature for $ $0°C and $ $10°C ranged from $2160.2-5226.2°C \cdot d$ and $1330.9-4655.1°C \cdot d$ respectively, showing a west-low-east-high pattern. High-value areas were concentrated in the Fenwei Plain, particularly at Yushe and Yuanping stations, while low-value areas were in the southwestern Qinghai-Tibet Plateau ecological region, especially at Xining, Taole, and Haiyuan stations.

Most stations (94.5%) showed highly significant increasing trends (P<0.01), with the most significant increases at Yushe Station ($12.92°C \cdot d \cdot a^{-1}$) and Yuanping Station ($13.41°C \cdot d \cdot a^{-1}$). Xiji Station showed a non-significant increasing trend (P>0.05). Compared with 1960-1989, active accumulated temperature during 1990-2019 was $56.98-392.50°C \cdot d$ and $44.42-421.60°C \cdot d$ higher respectively, with the most significant increases at Yuanping Station. The spatial distribution pattern of these anomalies was similar to the trend patterns, showing an east-high-west-low pattern, with the $250-300°C \cdot d$ anomaly range being most widespread.

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3 Discussion

3.1 Impacts of Accumulated Temperature Indicator Changes on the Loess Plateau

Under global warming, various accumulated temperature indicators (such as $ $0°C, $ $10°C, $ $15°C, $ $20°C) across China [11-13,15] and different regions [9-10,14-16] consistently showed trends of earlier first dates, later ending dates, longer duration, and increased active accumulated temperature, leading to significant phenological changes in plants. Our study found that from 1960-2019, $ $10°C accumulated temperature indicators on the Loess Plateau showed similar trends to other regions in China [11], the Yellow River Basin [35], and Tibet [8], but with some differences. The advancement of first dates was more pronounced than the national average, while the delay of ending dates was comparable. The delay magnitude for $ $10°C ($0.130d \cdot a^{-1}$) was significantly higher than the national average ($0.078d \cdot a^{-1}$) [11]. Bai et al. [11] noted that the interval days between $ $0°C and $ $10°C first dates decreased significantly across China, while our study found this interval decreased at a rate of $0.028d \cdot a^{-1}$ on the Loess Plateau, indicating more intense changes than the national average.

The interval days between ending dates remained stable at 46.79 d, decreasing from 43.43 d in the 1960s to 42.16-42.93 d in the 2010s. Under the combined effect of earlier first dates and later ending dates, duration days for both thresholds extended at rates of $0.288d \cdot a^{-1}$ and $0.314d \cdot a^{-1}$ respectively (P<0.01), both slightly higher than the national average [11] but much lower than the Tibetan Plateau [8], indicating a significant response to global warming on the Loess Plateau.

Changes in accumulated temperature indicators on the Loess Plateau have caused earlier spring sowing dates for thermophilic crops and delayed winter sowing dates for chill-tolerant crops [37], increasing multiple cropping potential [38]. However, these changes may also expand and intensify crop pests and diseases [39], increasing agricultural production costs.

During the global warming hiatus (1998-2012), the average temperature on the Loess Plateau decreased at a rate of $0.049°C \cdot a^{-1}$ (P>0.05), and \$ \$10°C accumulated temperature showed delayed first dates, shortened duration, and decreased active accumulated temperature. However, the average temperature in 2019 reached 9.54°C, higher than the 8.53°C before the hiatus, indicating that accumulated temperature indicators on the Loess Plateau have significant phased characteristics.

Sub-regional analysis revealed distinct differences among ecological-geographical sub-regions. The East Asian Monsoon Sub-region had the earliest first dates, latest ending dates, longest duration, and highest active accumulated temperature for \$ \$10°C. The Northwest Arid and Qinghai-Tibet Plateau sub-regions had similar first dates, ending dates, and duration, but were much earlier (later) and shorter (longer) than the East Asian Monsoon Sub-region. The active accumulated temperature in the Northwest Arid Sub-region was much higher than in the East Asian Monsoon Sub-region. These differences suggest that future research should combine high spatio-temporal resolution temperature data to explore accumulated temperature variation patterns in different sub-regions of the Loess Plateau.

3.2 Relationship Between Accumulated Temperature Indicators and Geographical Factors on the Loess Plateau

Studies show that meteorological elements such as temperature, ground temperature, and accumulated temperature exhibit significant regional differences closely related to latitude, longitude, and altitude [40]. Correlation analysis between accumulated temperature indicators and geographical factors on the Loess Plateau (Table 5) shows that first dates are significantly positively correlated with longitude (α=0.001) and significantly negatively correlated with latitude (α=0.001), while ending dates and duration days are significantly negatively correlated with latitude (α=0.001). This indicates that lower latitudes correspond to earlier first dates, later ending dates, and longer duration. Except for first dates, all other indicators are significantly positively correlated with longitude (α=0.01), indicating that more easterly locations have later ending dates, longer duration, and higher active accumulated temperature—a pattern different from the weak correlation between Tibetan Plateau accumulated temperature indicators and longitude [8].

All accumulated temperature indicators are highly significantly correlated with altitude (α=0.001), consistent with Du et al.'s [8] findings for Tibet. Dominance analysis revealed that changes in \$ \$10°C first dates, ending dates, and duration days were jointly influenced by latitude and altitude, while other indicators were primarily affected by altitude with contribution rates of 65.59%-72.17%. Altitude' s contribution to active accumulated temperature was higher than the 55.60%-58.90% reported for the Tibetan Plateau [8]. Evidence suggests that elevation-dependent warming exists in Northwest China, with the most significant warming occurring at 1000-2000 m altitude on the Loess Plateau [42], making altitude the dominant factor affecting accumulated temperature changes. Human activities, including greenhouse gas emissions and urbanization levels, have caused rapid warming globally and in China [16,43], inevitably affecting temperature resources on the Loess Plateau. Future research should further quantify the impacts of human activities on accumulated temperature changes.

3.3 Impact Degree of First Date and Ending Date Changes on Duration Changes

Dominance analysis was used to calculate the contribution rates of longitude, latitude, and altitude to changes in accumulated temperature indicators on the Loess Plateau (Table 5). The results show that changes in $ $10°C first dates, ending dates, and duration days were mainly influenced by latitude and altitude, consistent with correlation analysis results. Other indicators were primarily affected by altitude.

Further analysis revealed that the contribution rate of first date changes to duration changes for $ $10°C accumulated temperature was 65.1% during 1960-2019, decreasing slightly from 59.7% in 1960-1989 to 57.4% in 1990-2019. For $ $0°C, the contribution rate was 68.4%, increasing significantly from 52.1% in 1960-1989 to 67.3% in 1990-2019. This indicates that the extension of duration days for both thresholds on the Loess Plateau was mainly caused by significant advancement of first dates.

The contribution rates of first date changes to duration changes at individual stations showed a decreasing trend from east to west, with the highest values (up to 81.6%) in the northeastern part of the study area. The spatial pattern was generally high in the south and west, and low in the central and northeastern regions. The Longdong Plateau and Fen River Valley had the highest values, while the Guide station even reached 81.6%, indicating complex influences on duration changes. Notably, 15 stations (including Yushe, Guyuan, and Xiji) had contribution rates below 50% for $ $10°C, indicating that duration changes at these stations were mainly influenced by ending date changes.

Compared with 1960-1989, the contribution rates of first date changes to duration changes during 1990-2019 showed a "high-low-high"alternating pattern from south to north, with the most significant change at Yuzhong Station (-31.9%). For $ $0°C, the pattern was high in the southeast and low in the northwest, with the most significant change at Yuncheng Station (32.8%). This suggests that attention should be paid to the varying influence degrees of first date changes on duration changes across different regions and periods.

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4 Conclusions

Using daily average temperature data from 55 meteorological stations from 1960-2019, and employing linear fitting, mutation tests, dominance analysis, and spatial visualization, this study analyzed the spatio-temporal variation characteristics of $ $0°C and $ $10°C accumulated temperature indicators on the Loess Plateau. The main conclusions are:

1. **Temporal characteristics:** From 1960-2019, first dates for both thresholds advanced at rates of $0.186d \cdot a^{-1}$ and $0.158d \cdot a^{-1}$; ending dates delayed at rates of $0.130d \cdot a^{-1}$ and $0.128d \cdot a^{-1}$; duration days extended at rates of $0.288d \cdot a^{-1}$ and $0.314d \cdot a^{-1}$; and active accumulated temperature increased at rates of $7.50°C \cdot d \cdot a^{-1}$ and $7.55°C \cdot d \cdot a^{-1}$. All trends were highly significant ($P<0.01$). Interdecadal shifts mostly occurred in the 1990s, with abrupt changes concentrated in the late 1990s to early 2000s, and duration days and active accumulated temperature showed the earliest mutation times.

2. **Spatial characteristics:** The multi-year average values showed consistent spatial distributions, with first dates advancing, ending dates delaying, duration extending, and active accumulated temperature increasing from northwest to southeast. However, spatial patterns of trend magnitudes differed: first date advancement showed a "high-low-high" pattern along the southeast-northwest direction; ending date delay showed a "high-low" alternating pattern along the east-west direction; active accumulated temperature increase showed an east-high-west-low pattern; and duration extension showed a west-high-east-low pattern.

3. **Influencing factors:** Changes in $ $10°C first dates, ending dates, and duration days were jointly influenced by latitude and altitude, while other indicators were primarily affected by altitude with contribution rates of 65.59%-72.17%. The contribution rates of first date changes to duration changes were 65.1% for $ $10°C and 68.4% for $ $0°C, showing a decreasing trend from east to west and a spatial pattern of high in the southeast and low in the northwest.

4. **Period comparison:** Compared with 1960-1989, most indicators (except first dates) showed unchanged trend directions but more pronounced magnitudes of change during 1990-2019.

Overall, accumulated temperature indicators for both thresholds on the Loess Plateau respond significantly to climate warming, with distinct regional and temporal characteristics.

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