

Article

Spatial–Temporal Variations in Frost-Free Days During 1961–2023 in Qinghai Province, China

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Abstract

Rational development and utilization of climate resources are essential for mitigating frost disasters, particularly in high-altitude regions. This study investigates the spatiotemporal characteristics of frost events in Qinghai Province to improve understanding of frost evolution under climate change. Daily minimum temperature data from 51 meteorological stations from 1961 to 2023 were analyzed to determine the first frost date (FFD), last frost date (LFD), and frost-free period (FFP), along with their trends and influencing factors. Results show that the mean FFD, LFD, and FFP were 5 October, 14 May, and 144 days, respectively. Over the past six decades, LFD advanced, whereas FFD was delayed, leading to a marked extension of FFP, with trends of 2.08, 2.87, and 4.68 days per decade, respectively. These changes became more pronounced after the 1990s. Spatially, lower-altitude regions exhibited later FFD, earlier LFD, and longer FFP, whereas higher-altitude regions showed the opposite pattern. Correlation analysis indicates that frost characteristics are most strongly influenced by altitude, followed by latitude and longitude. Overall, climate warming has shortened the frost season and extended the growing period in Qinghai Province. These findings provide a scientific basis for optimizing agricultural zoning, adjusting cropping systems, and improving climate resilience in cold, high-altitude regions.

Keywords: first frost date; last frost date; frost-free period; spatiotemporal variations; Qinghai Province

1. Introduction

In meteorology, frost is a weather phenomenon that occurs when the temperature at or near the ground surface drops to approximately 0 °C, causing water vapor in the surrounding air to condense and form white ice crystals on surfaces or objects. This type of frost is generally harmless to crops [1]. In agriculture, however, frost refers to the freezing injury of plants that occurs when the temperature of plant tissues falls below 0 °C during the growing season, leading to damage that is considered an agricultural meteorological disaster [2]. However, plant temperature is difficult to measure directly. Therefore, the daily minimum temperature or the daily minimum temperature at 0 cm above the ground is typically used as a proxy, with frost damage considered to occur when these temperatures fall below 0 °C. Frost seriously affects normal agricultural activities, and severe frost damage causes an approximately 30% reduction in crop yield or even complete crop failure [3].



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For agricultural purposes, the first date in autumn with a ground minimum temperature $\leq 0\text{ }^{\circ}\text{C}$ is defined as the first frost date (FFD), while the last such date in spring is the last frost date (LFD). The number of days between them constitutes the frost period [4]. The frost-free period (FFP) is an important indicator of the amount of heat resources in a region [5,6]. The length of the FFP is determined based on the FFD and LFD. Changes in the FFP directly affect the probability and degree of crop damage. Therefore, analyzing the climatic characteristics of FFD, LFD, and FFP is important for the agricultural sector in combating crop damage.

According to the IPCC AR6, each of the last four decades has been successively warmer than any preceding decade since 1850. The global surface temperature during the first two decades of the 21st century (2001–2020) was $0.99\text{ }^{\circ}\text{C}$ higher than that during 1850–1900 [7]. Owing to climate warming, research on changes in frost dates and periods has garnered widespread attention [8,9]. Numerous studies have confirmed that climate warming influences the timing of the FFD and LFD, thereby altering the length of the frost season [10–14].

Bonsal et al. [15] and Heino et al. [16] observed a decreasing trend in the number of frost days in Canada and Northern Europe, respectively. Anandhi et al. [17] selected six frost indices to study past and future frost changes in the Catskill Mountains of New York City (USA). The results showed that the average frost day, last frost day, first frost day, and length of the growing season exhibited decreasing, advancing, delaying, and prolonging trends, respectively, in the past and future periods. Erilat and Türkeş [18] found that frost days in most parts of Türkiye showed a substantial decreasing trend based on the criterion of a daily minimum temperature $\leq 0\text{ }^{\circ}\text{C}$. Easterling [19] used a daily minimum temperature $< 0\text{ }^{\circ}\text{C}$ as the condition for frost occurrence. They found that the number of frost days in the continental United States decreased at a rate of approximately 0.8 days per decade over the past 50 years. Similarly, in China, research indicates a national pattern of delayed FFDs, advanced LFDs, prolonged FFPs, and a significant reduction in frost days [20,21]. Analysis of variations in daily minimum temperature revealed that the number of frost days in most parts of China showed a marked decreasing trend. Qian and Lin [22] reported that the frost period in northern China has gradually shortened. The same is true in Jilin [23], Gansu [24], the Huaihe River Basin [3], and the Loess Plateau [25] in China. These results indicate that the number of frost days worldwide is decreasing to varying degrees due to global warming.

The Qinghai–Tibet Plateau represents the upper altitudinal limit for cultivating multiple crops in China and is characterized by a distinct farming boundary [26]. With climate warming, the growing intensity of extreme weather conditions, coupled with frequent human activities, has heightened uncertainty in local agricultural production. As a key component of the Qinghai–Tibet Plateau, Qinghai Province provides an ideal setting for investigating frost responses to climate change. Its high altitudinal gradient, high sensitivity to climate change, fragile agroecological environment, and potentially distinct response to global warming relative to lower-altitude regions make it a natural laboratory for monitoring climate change on the plateau and elucidating the mechanisms underlying frost dynamics.

Qinghai Province is located in the northeast Qinghai–Tibet Plateau, where the terrain is high in the west and low in the east. The climate is primarily alpine and arid, representing a typical plateau continental climate. Changes in frost have significant impacts in Qinghai Province, particularly when the first frost occurs abnormally early, and the last frost is significantly delayed. These anomalies can cause severe damage to vegetation during the early and late stages of growth and development in spring and autumn. Currently, only a few studies on frost have been conducted in Qinghai Province. Based on the

meteorological data of 51 provincial meteorological stations collected from 1961 to 2023, this study systematically and comprehensively analyzed the variation characteristics of FFD, LFD, and FFP in Qinghai Province. The findings aim to support agricultural and animal production practices in this region, enhance the capacity for frost-disaster prevention and early warning, and provide a scientific basis for disaster prevention and mitigation efforts by relevant agricultural departments.

2. Materials and Methods

2.1. Site Description

The study was conducted in Qinghai ($89^{\circ}35'–103^{\circ}04'$ E, $31^{\circ}39'–39^{\circ}19'$ N), in the northeastern part of the Qinghai–Tibet Plateau (Figure 1). The region is characterized by an extended cold period, intense solar radiation, large diurnal temperature variations, drought, low rainfall, and concentrated precipitation events. In Qinghai, the average annual precipitation ranges from 18.0 to 742.1 mm, the average temperature ranges from -4.6 to 9.5 °C, and the annual solar radiation ranges from 5400 to 7600 MJ·m⁻².

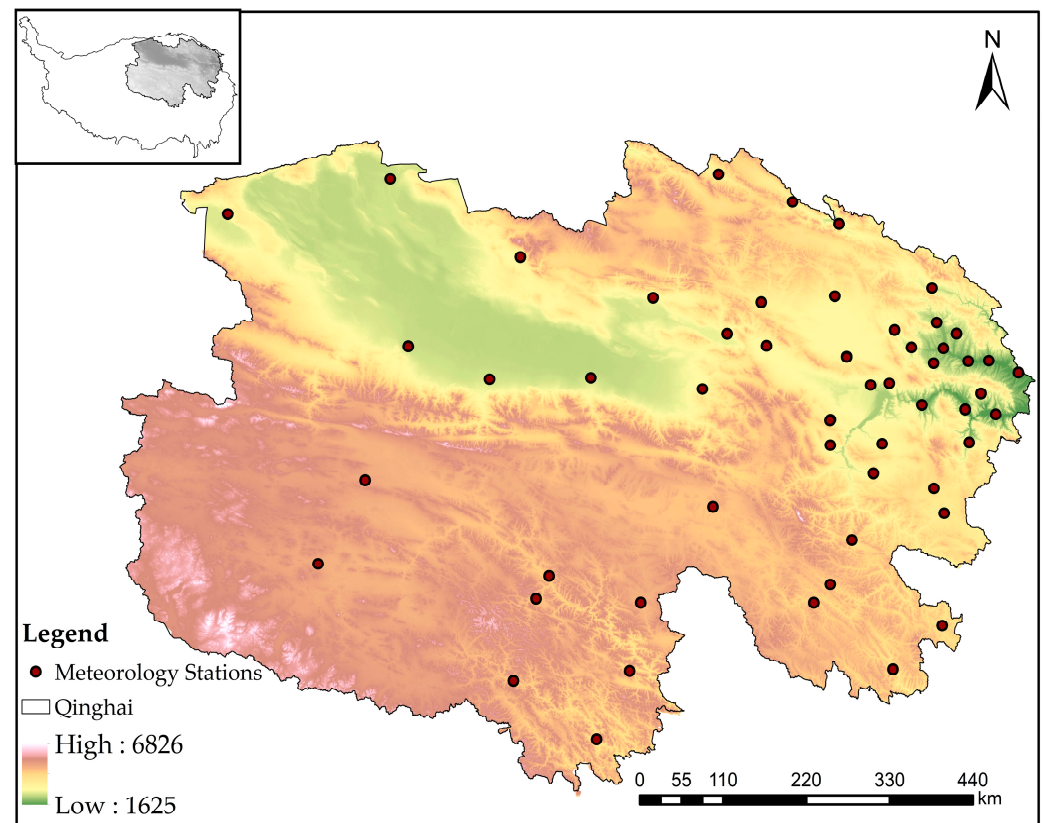


Figure 1. Distribution of meteorological stations in the study area.

2.2. Meteorological Data

This study analyzed three key agroclimatic indices pertaining to the thermal growing season: FFD, LFD, and FFP. To maintain observational consistency, the analysis was based on the daily minimum ground temperature (measured at 0 cm height above the ground) dataset, spanning 1961 to 2023, obtained from 51 surface meteorological stations across Qinghai Province. This dataset was provided and quality-controlled by the Qinghai Meteorological Information Center.

The three indices were calculated according to the following standard agrometeorological definitions: FFD: The first day within a given calendar year (from 1 July onward) on which the daily minimum temperature falls below 0 °C. LFD: The last day within a

given calendar year (up to 30 June) on which the daily minimum temperature falls below 0 °C. FFP: The number of days between the LFD of the current spring and the FFD of the following autumn. Specifically, it is calculated as $FFP = FFD - LFD + 1 \text{ yr}$, where “yr” can be defined as 365 days, ensuring that both dates pertain to the same thermal growing season cycle.

2.3. Statistical Analysis

2.3.1. Trend-Free Prewhitening and Theil–Sen Slope Estimator

Trend-Free Prewhitening (TFPW) is a pre-whitening Mann–Kendall (MK) trend test method used to address autocorrelation in the time series under analysis. The procedure involves two steps: detrending and pre-whitening, which can effectively reduce the influence of autocorrelation in the sequence on the test results and prevent distortion. The procedure is described as follows [27]:

$$Y_t = X_t - \beta \cdot t \quad (1)$$

$$Y_t' = Y_t - r \cdot Y_{t-1} \quad (2)$$

$$Y_t'' = Y_t' + \beta \cdot t \quad (3)$$

$$\beta = \text{Median}\left(\frac{x_i - x_j}{i - j}\right), 1961 \leq j \leq i \leq 2023 \quad (4)$$

where Y_t is the residual sequence after removing the trend; Y_t' is a white-noise-like sequence obtained after removing autocorrelation; and Y_t'' is the reconstructed sequence obtained after TFPW processing. β is the estimated slope from the Theil–Sen estimator [28]. When $\beta > 0$, the time series indicates an increasing trend, whereas $\beta < 0$ indicates a decreasing trend. The trend rate is expressed in days per decade (d/10 a). r is the first-order autocorrelation coefficient of Y_t . It should be noted that if r is sufficiently small, Y_t can be considered an independent sequence and be directly used in the standard MK test without preprocessing. Otherwise, the preprocessing steps in Equations (2) and (3) should be applied before performing the MK test on Y_t'' .

2.3.2. MK Test

The MK rank statistic is considered most appropriate for analyzing trends in climatological time series [29]. In the present study, the MK test was used to analyze the significance of the trends in FFD, LFD, and FFP. The test was used to determine whether the trends in these three agroclimatic indices were statistically significant. The test statistics were as follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & (S > 0) \\ 0 & (S = 0) \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & (S < 0) \end{cases} \quad (5)$$

where $S = \sum_{j=1}^{n-1} \sum_{i=j+1}^n \text{sgn}(M_j - M_i)$

$$\text{sgn}(M_j - M_i) = \begin{cases} 1 & (M_j - M_i > 0) \\ 0 & (M_j - M_i = 0) \\ -1 & (M_j - M_i < 0) \end{cases} \quad (6)$$

$$\text{Var}(S) = \frac{n(n-1)(2n+5)}{18}, \quad (7)$$

where M_j represents the FFD, LFD, or FFP in year j , and M_i represents the values in year i ; n denotes the number of observations (63 years for the period 1961–2023). A positive Z-value indicates an increasing trend, whereas a negative Z-value indicates a decreasing

trend. Trends are considered statistically significant at the 95% and 99% confidence levels (5% and 1% significance levels, respectively).

The MK test involves the computation of two complementary statistics: the forward sequence (UF_k) and the backward sequence (UB_k). UF_k ($k = 1, 2, \dots, n$) is computed sequentially in the original chronological order as the standardized MK test statistic, with UF_1 set to 0. UF_k asymptotically follows a standard normal distribution. UB_k is obtained by applying the same procedure to the reversed time series and then multiplying the resulting standardized statistic by -1 . If the UF and UB curves intersect and the intersection point lies within the critical bounds, the corresponding time point is identified as a potential change point. Moreover, UF or UB values greater than 0 indicate an upward trend, whereas those less than 0 indicate a downward trend. When either curve exceeds the critical lines, the trend is considered statistically significant [30].

2.3.3. Pettitt Test

In contrast to the UF–UB procedure, the Pettitt test identifies the most probable change point and provides its statistical significance (p -value), making the results more objective and easier to interpret. This non-parametric method detects abrupt shifts in the mean of a time series using a rank-based approach [31]. The method consists of three steps: (i) computation of the statistic $U_{t,n}$, (ii) derivation of $K_{t,n}$ to identify the potential change point, and (iii) assessment of statistical significance. The corresponding formulas are presented in Equations (8)–(10).

$$U_{t,n} = U_{t-1,n} + \sum_{i=1}^n \text{sgn}(x_t - x_i) \quad (t = 2, 3, \dots, n) \quad (8)$$

$$K_{t,n} = \max |U_{t,n}| \quad (1 \leq t \leq n) \quad (9)$$

$$p = 2 \exp \left[-6K_{t,n}^2 / (N^3 + N^2) \right] \quad (10)$$

when $p \leq 0.05$, the change point is considered statistically significant. This method is robust to outliers and skewed distributions and provides a clear quantification of the significance [31].

2.3.4. Partial Correlation Coefficient

Partial correlation coefficients were calculated to assess the relationship between frost indices and altitude, longitude, and latitude at meteorological stations in Qinghai Province, while controlling for the confounding effects among these geographical variables. Statistical significance was set at $p < 0.05$. The formula is described as follows:

$$r_{12,3} = \frac{r_{12} - r_{13}r_{23}}{\sqrt{(1 - r_{13}^2)(1 - r_{23}^2)}} \quad (11)$$

where r_{12} , r_{13} , and r_{23} represent the correlation coefficients among the three variables, and $r_{12,3}$ is the partial correlation coefficient between variables 1 and 2 after removing the effect of variable 3.

2.3.5. Multiple Regression Analysis

Multiple regression analysis was performed to assess the relative contributions of individual explanatory variables [32]:

$$Y_F = a_1x_1 + a_2x_2 + a_3x_3 + b \quad (12)$$

where Y_F is the frost index (FFD, LFD, or FFP) predicted by the regression model; x_1 , x_2 , and x_3 represent altitude, longitude, and latitude, respectively; a_1 , a_2 , and a_3 are the corresponding regression coefficients; and b is the intercept.

2.3.6. Regression Interpolation

Regression interpolation was employed to develop statistical relationships between the frost indices (FFD, LFD, and FFP) and the DEM. The derived relationships were subsequently applied across Qinghai Province to produce continuous spatial surfaces with a 30 m resolution.

3. Results

3.1. Temporal Trend Analysis

As shown in Figure 2, the average FFD in Qinghai Province during 1961–2023 occurred on 5 October. The earliest FFD occurred on 24 September 1965, whereas the latest occurred on 20 October 2016, with a significant delay of 2.08 d/10 a according to the linear regression analysis. The average LFD was 14 May, ranging from 30 April 2020 (earliest) to 29 May 1961 (latest), and advanced significantly at 2.87 d/10 a. The average FFP was 144 days, varying from 123 days (1961) to 170 days (2020), and increased significantly at 4.68 d/10 a.

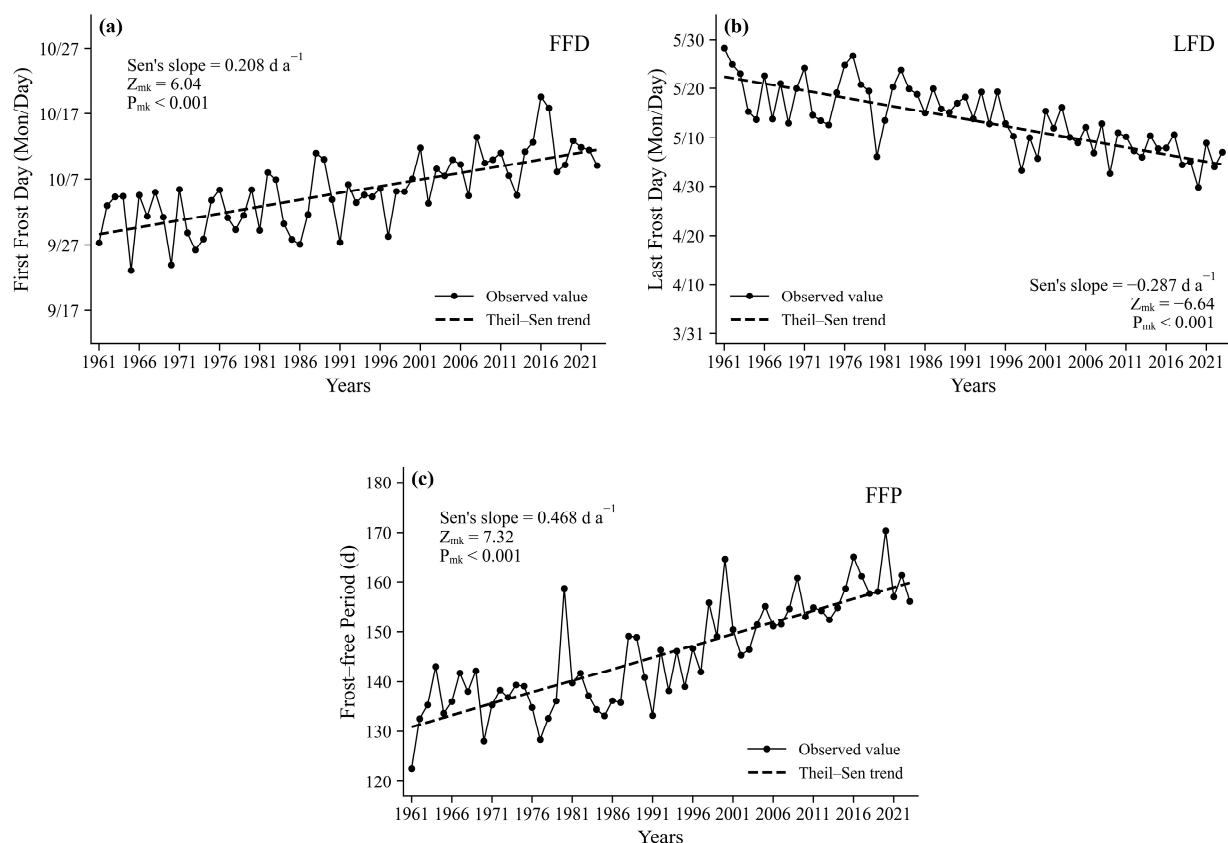


Figure 2. Annual variation in the (a) first frost date, (b) last frost date, and (c) frost-free period in Qinghai Province from 1961 to 2023.

The trends in FFD, LFD, and FFP during 1961–1990 and 1991–2020 are consistent with those observed over the full period (1961–2023) (Table 1): FFD was delayed, LFD advanced, and FFP was prolonged. However, none of these trends were statistically significant during 1961–1990, whereas all were significant during 1991–2020, with rates of change markedly exceeding those for the entire study period.

Table 1. FFD, LFD, and FFP trends during each WMO reference period in Qinghai Province (d/10 a).

	FFD	LFD	FFP
1961–1990	1.36	−1.46	2.09
1991–2020	3.73 **	−3.60 **	7.36 **
1961–2023	2.08 **	−2.87 **	4.68 **

** indicates that the slope is significant at the 99% significance level. FFD, first frost date; LFD, last frost date; FFP, frost-free period; WMO, World Meteorological Organization

Across the four functional areas of Qinghai Province (Table 2), the FFD was also significantly delayed, the LFD advanced, and the FFP prolonged. The rates of FFD delay, LFD advancement, and FFP prolongation were largest in the Qaidam Basin, at 2.74, 3.31, and 5.98 d/10 a, respectively. In contrast, the delay rate of the FFD, the advancement rate of the LFD, and the prolongation rate of the FFP in the Three-River Source Area were 1.66, 2.44, and 4.18 d/10 a, respectively, representing the lowest rates among these indices.

Table 2. FFD, LFD, and FFP trends in different functional areas of Qinghai Province from 1961 to 2023 (d/10 a).

	East Agriculture Area	Qaidam Basin	Qilian Mountains	Three-River Source River
FFD	2.36 **	2.74 **	1.84 **	1.66 **
LFD	−2.87 **	−3.31 **	−2.49 **	−2.44 **
FFP	5.19 **	5.98 **	4.41 **	4.18 **

** indicates that the slope is significant at the 99% significance level. FFD, first frost date; LFD, last frost date; FFP, frost-free period.

As indicated in Table 3, in Qinghai Province, the FFD from the 1960s to the 1990s occurred earlier than those in the post-2000 period and earlier than the average over the entire study period. The LFD from the 1960s to the 1980s occurred later than those after the 1990s and later than the long-term average. The FFP in the 1990s was equal to the 1961–2023 average and subsequently exceeded it.

Table 3. Ten-year means of the FFD, LFD, and FFP in Qinghai Province and the four functional areas.

Area		1961–1970	1971–1980	1981–1990	1991–2000	2001–2010	2011–2023	1961–2023
Qinghai Province	FFD	10/1	10/2	10/4	10/4	10/9	10/12	10/6
	LFD	5/20	5/19	5/18	5/13	5/11	5/7	5/14
	FFP	134	136	139	144	151	157	144
Eastern Agriculture Area	FFD	10/17	10/17	10/19	10/20	10/24	10/28	10/21
	LFD	4/26	4/26	4/24	4/21	4/18	4/12	4/21
	FFP	173	174	178	182	188	199	183
Qaidam Basin	FFD	9/28	9/30	10/4	10/7	10/11	10/11	10/6
	LFD	5/19	5/14	5/14	5/8	5/3	5/3	5/10
	FFP	133	139	143	152	161	161	149
Qilian Mountains	FFD	9/18	9/20	9/21	9/21	9/27	9/28	9/23
	LFD	6/4	6/7	6/1	5/31	5/29	5/24	5/31
	FFP	106	105	111	113	121	127	115
Three-River Source River	FFD	9/22	9/24	9/26	9/23	9/29	10/2	9/26
	LFD	6/8	6/8	6/6	6/2	6/1	5/28	6/3
	FFP	106	108	111	113	120	127	115

FFD, first frost date; LFD, last frost date; FFP, frost-free period.

In the Eastern Agricultural Area, the average FFD from 1961 to 2023 was 21 October, which was later than the average FFD from the 1960s to the 1990s and earlier than the average after the 2000s. The average LFD occurred on April 21, which was earlier than the average from the 1960s to the 1980s. The average FFP during the study period was 183 days, which was longer than the average FFP from the 1960s to the 1990s.

In the Qaidam Basin Area, the average FFD during 1961–2023 occurred on 6 October, which was later than the average FFD from the 1960s to the 1980s and earlier than the average after the 1990s. The average LFD occurred on 10 May, which was earlier than the average value from the 1960s to the 1980s and later than the average LFD after the 1990s. The average FFP was 149 days, which was longer than the average from the 1960s to the 1980s and shorter than the value after the 1990s.

In the Qilian Mountain Area, the FFD occurred on 23 September, which was later than the 1960s–1990s average and earlier than the average after the 2000s. The average LFD occurred on 31 May, which was earlier than the 1960s–1980s average, similar to that of the 1990s, and later than the average after the 2000s. The average FFP was 115 days, which was longer than the 1960s–1990s average.

In the Three-River Source River Area, the average FFD occurred on 26 September, which was later than the 1960s–1990s average and earlier than the average after the 2000s. The average LFD occurred on 3 June, which was earlier than the 1960s–1980s average and later than the average after the 1990s. The average FFP was 115 days, which was longer than the 1960s–1990s average.

3.2. Spatial Characteristics Analysis

3.2.1. Spatial Distribution Characteristics of Frost Dates

From 1961 to 2023, the spatial distribution of the FFD and LFD in Qinghai Province gradually advanced from east to west, whereas FFP gradually shortened from east to west (Figure 3). The FFD in Qinghai Province occurred between 5 September and 4 November. The FFDs at the Minhe, Xunhua, Jianzha, Ping'an, and Ledu stations were the latest, occurring after 28 October. The FFDs were earliest at six stations, including Wudaoliang, Tuole, Qingshuihe, Yeniugou, Maduo, and Tuotuohe, occurring before 13 September (Figure 3a). The LFD in Qinghai Province was between 27 March and 6 July, while the LFDs at the Wudaoliang, Tuotuohe, and Qingshuihe stations were the latest, occurring after 23 June. The LFDs at the Minhe, Xunhua, and Jianzha stations were the earliest, occurring on 30 March (Figure 3b). The average FFPs in Qinghai Province ranged from 61 and 222 days, while those in Minhe, Xunhua, Jianzha, Ping'an, and Ledu exceeded 206 days. The FFPs at the Wudaoliang, Qingshuihe, and Tuotuohe stations were less than 80 days (Figure 3c).

3.2.2. Spatial Distribution Characteristics of Frost Trend

The spatial distribution of frost trends across the 51 stations in Qinghai Province from 1961 to 2023 is shown in Figure 4. The FFD showed a delayed trend, with a delay rates ranging from 2.19 to 4.51 d/10 a. Approximately 61% of the stations showed a strongly significant delayed trend ($p < 0.01$), while 20% showed a delayed trend significant at the lower threshold of $p < 0.05$. Qinghai Lake 151, Mangai, and Tongde stations had the fastest delay rates, higher than 4.37 d/10 a. Xining and Tuole had the slowest delay rates, below 0.29 d/10 a (Figure 4a).

The LFD exhibited an advancing trend, with advance rates ranging from 0.41 to 5.55 d/10 a. Approximately 67% of the stations exhibited a strongly significant advancing trend, while 22% displayed a significant advancing trend. The Mangai, Tongde, Qinghai Lake 151, and Wudaoliang had the fastest advance rates, exceeding 4.17 d/10 a. Hua-

long, Xining, Guinan, and Xinghai had the slowest advance rates, which were less than 0.96 d/10 a (Figure 4b).

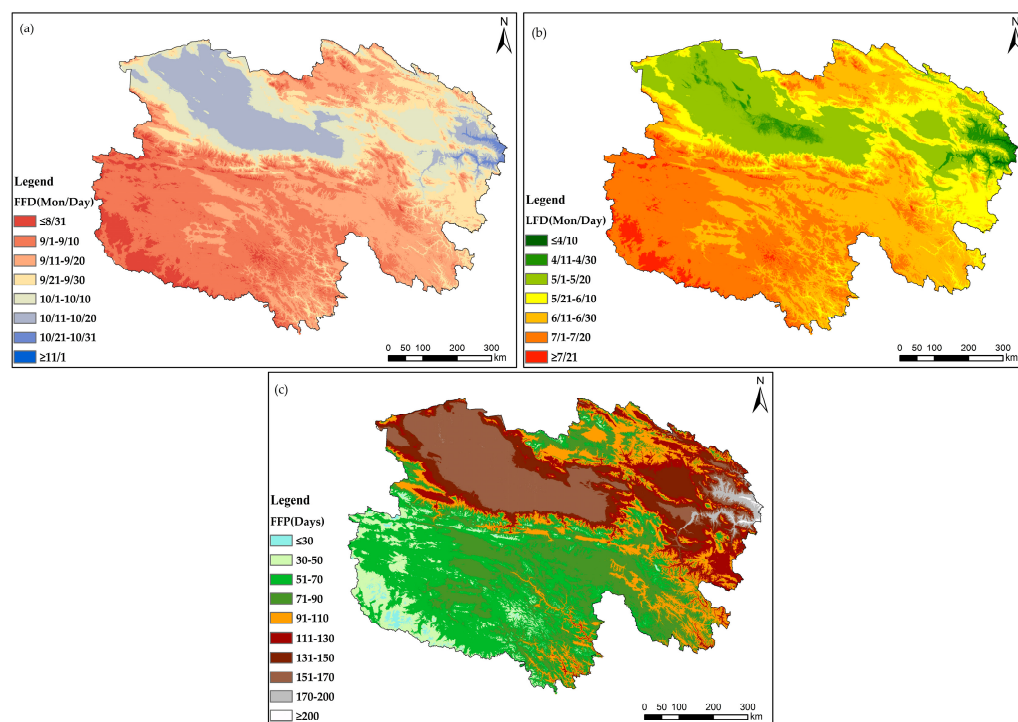


Figure 3. Spatial distribution of (a) FFD, (b) LFD, and (c) FFP trend coefficients in Qinghai Province from 1961 to 2023. FFD, first frost date; LFD, last frost date; FFP, frost-free period.

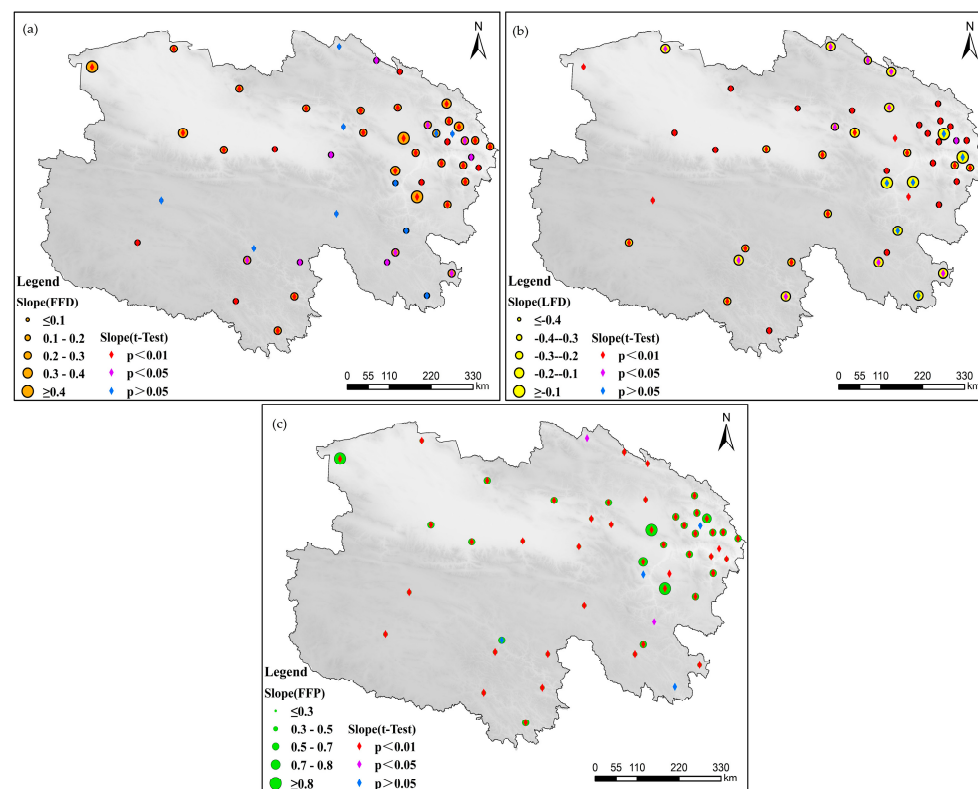


Figure 4. Spatial distribution of (a) FFD, (b) LFD, and (c) FFP period trends in Qinghai Province from 1961 to 2023. FFD, first frost date; LFD, last frost date; FFP, frost-free period.

The FFP extension rate ranged from 0.82 and 10.00 d/10 a, showing an increasing trend. Among all stations, 82% displayed a strongly significant extension trend, while 4% exhibited a significant extension trend (Figure 4c). The Xining and Xinghai had the slowest extension, below 1.57 d/10 a, whereas the Qinghai Lake 151, Tongde, and Mangai had the fastest extension rates, exceeding 8.40 d/10 a (Figure 4c).

3.3. Change Point Characteristics

The MK mutation test curves for the FFD, LFD, and FFP in Qinghai Province from 1961 to 2023 are shown in Figure 5. Over the past 63 years, the positive-sequence UF curve of the FFD in Qinghai Province showed an overall upward trend, whereas the inverse-sequence UB curve exhibited a downward trend. The two curves intersected in 1998, and the FFD change point was determined to be 1998. The average FFD occurred on 1 October before the change point and on 8 October after it, representing a delay of 7 days (Figure 5a). The positive-sequence UF curve of the LFD showed an overall downward trend, whereas the inverse-sequence UB curve displayed an upward trend. The two intersected in 2004, and the LFD change point was determined to be 2004. The average LFD occurred on 17 May before the change point and on 8 May after it, representing an advance of 9 days (Figure 5b). The positive-sequence UF curve of the FFP showed an overall upward trend, whereas the inverse-sequence UB curve showed a downward trend. The two intersected in 1999, and the FFP change point was determined to be 1999. The average FFP was 139 days before the change point and 156 days after the change point, representing an extension of 17 days (Figure 5c).

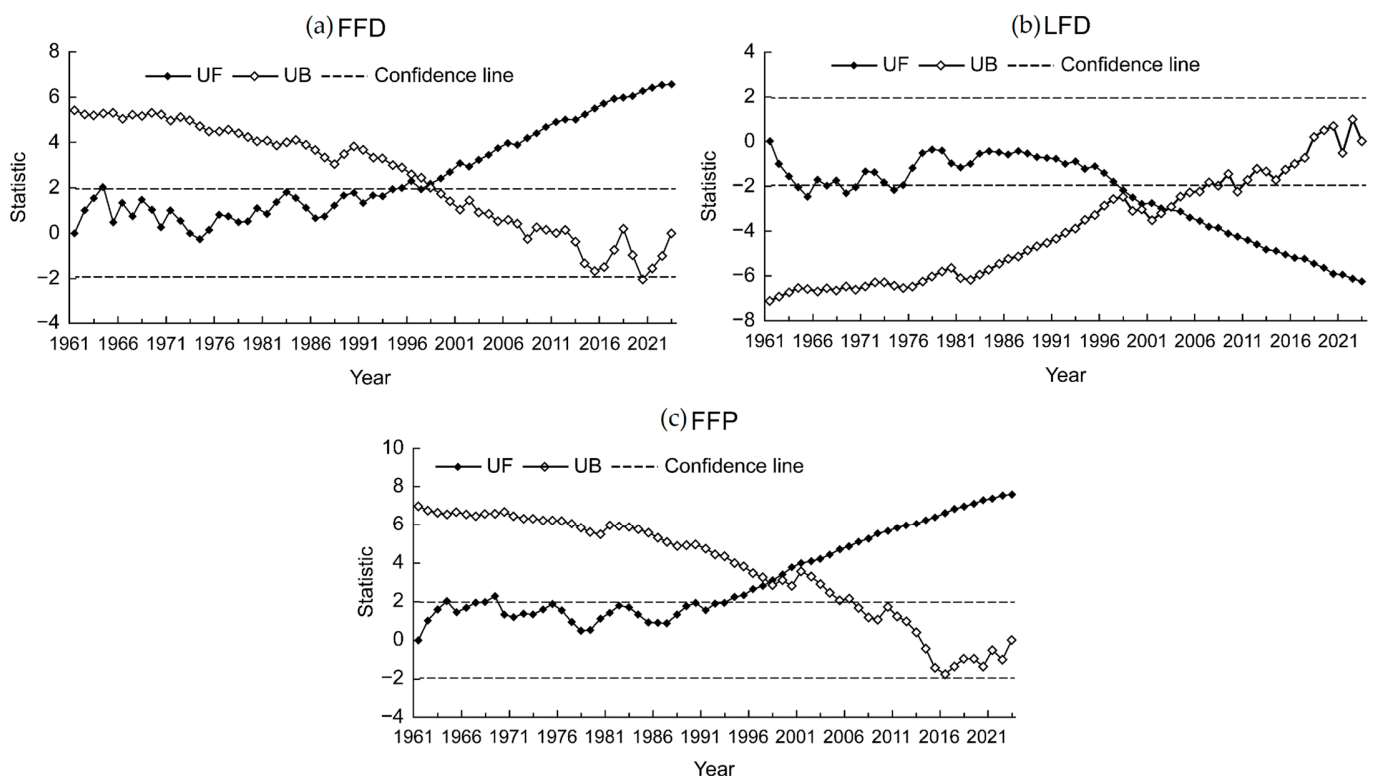


Figure 5. MK test curves of the (a) FFD, (b) LFD, and (c) FFP in Qinghai Province from 1961 to 2023. FFD, first frost date; LFD, last frost date; FFP, frost-free period.

As indicated in Table 4, significant abrupt changes were detected in all three factors based on the Pettitt test ($p < 0.01$). The FFD change-point year was 1997. The FFD was delayed from 2 October before the change point to 10 October after it, corresponding to an extension of 8 days. The rate of change increased from 1.25 d/10 a before the change point to 2.5 d/10 a afterward. A significant change point in the LFD occurred in 1995, with the

mean date advancing from 18 May to 9 May (a shift of 9 days), while the negative trend steepened from -1.37 to -2.12 d/10 a. Correspondingly, the FFP experienced a significant regime shift in 1995, increasing from 138 to 155 days (an increase of 17 days), with the trend slope increasing from 2.60 to 4.88 d/10 a. Overall, the rates of change for all three variables increased markedly before and after the change-point year, indicating that local thermal conditions became more responsive to regional climate warming during the later period.

Table 4. FFD, LFD, and FFP change points in Qinghai Province from 1961 to 2023.

	Change Point	Mean Value Before Change	Rate Before Change (d/10 a)	Mean Value After Change	Rate After Change (d/10 a)	Change Magnitude
FFD	1997 **	2 October	1.25 **	10 October	2.50 **	8
LFD	1995 **	18 May	-1.37 **	9 May	-2.12 **	-9
FFP	1995 **	138	2.60 **	155	4.88 **	17

** indicates that the slope is significant at the 99% significance level. FFD, first frost date; LFD, last frost date; FFP, frost-free period.

3.4. Influencing Factors

The correlation and regression coefficients between the FFD, LFD, FFP, and the geographical factors in Qinghai Province from 1961 to 2023 are shown in Table 5. The FFD showed significant positive correlations with longitude ($r = 0.385$) and latitude ($r = 0.069$). Higher longitudes and latitudes were associated with later FFD occurrence. The FFD and altitude exhibited a significant negative correlation, with the FFD gradually advancing with increasing altitude. Specifically, for every 10 m increase in altitude, the FFD advanced by 0.27 days (Table 6).

Table 5. Relationships between FFD, LFD, FFP, and geographical factors in Qinghai Province.

		Longitude	Latitude	Altitude
Correlation coefficient	FFD	0.385 **	0.069 **	-0.687 **
	LFD	-0.394 **	-0.215 **	0.811 **
	FFP	0.413 **	0.165 **	-0.807 **

** indicates that the slope is significant at the 99% significance level. FFD, first frost date; LFD, last frost date; FFP, frost-free period; Lo, longitude; La, latitude; Al, altitude.

Table 6. Multiple regression analysis between the FFD, LFD, FFP, and geographical factors in Qinghai Province.

Multiple Regression Analysis		Durbin-Watson	VIF		
			Longitude	Latitude	Altitude
FFD	$\text{FFD} = -0.66 \times \text{Lo} - 5.49 \times \text{La} - 0.03 \times \text{Al} + 624.32$	1.284	1.518	1.654	2.209
LFD	$\text{LFD} = 1.29 \times \text{Lo} + 6.61 \times \text{La} + 0.04 \times \text{Al} + 368.22$	1.215	1.514	1.652	2.197
FFP	$\text{FFP} = -1.94 \times \text{Lo} - 12.11 \times \text{La} - 0.07 \times \text{Al} + 992.29$	0.960	1.514	1.651	2.196

LFD was significantly negatively correlated with longitude ($r = -0.394$) and latitude ($r = -0.215$). Higher longitudes and latitudes were associated with earlier LFD occurrence. A significant positive correlation was observed between LFD and altitude; as altitude increased, the LFD was gradually delayed. For every 10 m increase in altitude, LFD was delayed by 0.43 days.

FFP exhibited significant positive correlations with longitude ($r = 0.413$) and latitude ($r = 0.165$). Higher longitudes and latitudes were associated with longer FFPs. The FFP and altitude were significantly negatively correlated; the FFP gradually shortened with increasing altitude. For every 10 m increase in altitude, the FFP decreased by 0.70 days.

The regression diagnostics (Durbin–Watson and VIF) presented in Table 6 indicate that multicollinearity is not problematic (all VIFs < 2.21, well below the threshold of 10) and that residual autocorrelation is negligible (Durbin–Watson values close to 2, ranging from 0.96 to 1.28), thereby supporting the reliability of these regression estimates. The latitudinal and longitudinal influences on the FFD, LFD, and FFP were inconsistent with most research results. The observed divergence is primarily attributable to the unique topography of the region. The terrain in Qinghai is generally higher in the west and lower in the east, with elevated areas surrounding the Central Depression to both the north and the south. The western region features high and steep altitudes that descends eastward in a stepwise manner. The eastern region, which serves as a transition zone between the Qinghai–Tibet Plateau and Loess Plateau, is characterized by complex topography and diverse landforms.

4. Discussion

In the context of global warming, the FFD, LFD, and FFP have been significantly delayed, advanced, and prolonged, respectively, in the Loess Plateau [33], Yellow River Basin [34], North China [35], and Northern Xinjiang [36]. The present study found that the changes in the FFD, LFD, and FFP in Qinghai Province during 1961–2023 were greater than those in other regions, consistent with previous research results [37]. However, differences still exist among the three factors, and the rates of change in the LFD and FFP are generally greater than those in other regions [34–36,38]. The rate of change in the FFD is greater than that of most regions and slightly lower than that of individual sites [25,34]. This demonstrates that Qinghai, as an important part of the Qinghai–Tibet Plateau, is more sensitive to climate change than other regions. Overall, the changes in the FFD, LFD, and FFP were more beneficial than detrimental for agriculture and animal husbandry in Qinghai Province. The delay in the FFD, the advance of the LFD, and the extension of the FFP extended the crop-growing season, provided sufficient heat resources for regional agricultural production, and were conducive to expanding suitable crop planting areas and enhancing productivity. However, this phenomenon does not imply that climate change will reduce frost damage. On the contrary, it increases crop exposure to frost. The sensitivity of crop growth to frost varies with species and growth environment. After climate warming, the crop planting boundary shifted northward, the area of late-maturing varieties expanded, and multiple cropping indices increased. However, the heat demand of crops remained tightly balanced. Simultaneously, climate change and changes in planting structure have led to changes in the rhythm of crop growth and development, thereby increasing the risk of frost damage [21].

Compared with other regions in China [3,35,39,40], the extension rate of the FFP in Qinghai Province (4.68 d/10 a) exceeded that of the Loess Plateau (3.10 d/10 a), North China (3.85 d/10 a), Northeast China (4.08 d/10 a), and the Huaihe River Basin (4.38 d/10 a), but remained lower than that of the Tibet region (8.40 d/10 a). The delay rate of FFD in Qinghai (2.08 d/10 a) was lower than that in Tibet (5.1 d/10 a) and the Huaihe River Basin (2.15 d/10 a), but higher than that in North China (1.50 d/10 a), Northeast China (1.55 d/10 a), and the Loess Plateau (1.75 d/10 a). The advance rate of LFD in Qinghai (2.87 d/10 a) was lower than that in Tibet (3.3 d/10 a), but higher than that in Northeast China (2.50 d/10 a), the Huaihe River Basin (2.49 d/10 a), North China (2.32 d/10 a), and the Loess Plateau (2.2 d/10 a). These regional disparities are primarily attributable to the combined influence of multiple factors in Qinghai Province, which is located in the northeastern transitional zone of the Qinghai–Tibet Plateau. First, with an average elevation exceeding 3000 m, the high-altitude region is generally more sensitive to climate warming, resulting in more pronounced changes in frost-related variables. This explains why the rates of change in the FFD, LFD, and FFP in Qinghai are at the upper-middle level nationwide,

yet still lower than those observed in the higher-altitude Tibet region. Second, Qinghai has a typical continental climate, distinct from the eastern monsoon region influenced by oceanic conditions. The diurnal and annual temperature ranges are relatively large, and the underlying surface—dominated by alpine meadows, desert, and bare soil—has a high albedo, which further amplifies the effects of climate warming on frost-related variables.

Notably, the advance rate of the LFD in Qinghai was faster than the delay rate of the FFD. This asymmetry implies that spring warming exerts a stronger effect on advancing the LFD than autumn cooling has on delaying the FFD, indicating that the acceleration of spring temperature rise exceeds the deceleration of autumn cooling. From an agricultural perspective, the earlier advance of LFD in spring is favorable for the sowing and emergence of spring-sown crops; however, it also increases the risk of late spring coldness events, as crops sown too early may suffer more severe losses if exposed to anomalously low temperatures. The delayed onset of the FFD in autumn provides a longer growing period for late-maturing varieties and multiple-cropping systems, but it may also disrupt the traditional maturation and harvest schedules, leaving some crops vulnerable to early frost damage.

The impacts of frost changes on agriculture vary depending on crop species, growth stages, and planting regions. Major crops in Qinghai Province include spring wheat, highland barley, spring rapeseed, potato, and broad bean, each with different sensitivities and tolerances to frost. Although the overall trends identified in this study, namely, delayed FFD, advanced LFD, and prolonged FFP, favor an extended crop growing season from the perspective of annual heat resources, they do not necessarily imply a reduction in frost damage. On the contrary, the earlier LFD may encourage earlier sowing, while the delayed FFD may promote the adoption of late-maturing varieties. Under the combined influence of these two factors, the probability of crops encountering frost during critical growth stages may increase.

Frost changes also directly affect cropping systems and planting patterns in Qinghai Province. The gradient effect identified in this study, namely, a shortening of the FFP by 0.5 days per 10 m increase in elevation, has practical agricultural implications. With climate warming and the extension of the FFP, high-altitude areas that were previously unsuitable for certain crops due to an excessively short FFP may gain new planting opportunities. However, concurrently, the rates of FFD delay and LFD advance in these high-altitude regions are relatively slow, implying that crops still face considerable frost risk. Prolongation of the FFP creates favorable thermal conditions for increasing the multiple-cropping index and introducing high-value cash crops in the eastern agricultural zone of Qinghai Province. Nevertheless, such agricultural expansion is accompanied by increased exposure to climatic risk and should therefore be gradually implemented in practice.

Comparison of the rates of change in the FFD, LFD, and FFP in the four functional areas revealed that the Qaidam Basin, characterized by a dry climate, exhibited the highest rates of change. This was followed by the Eastern Agricultural Area, which has the largest human disturbance. Climate and human factors jointly affected changes in the FFD and LFD, with climate having the greater influence. Research indicates that these variations are primarily attributable to topography, geographical location, and cold air pathways [41]. Furthermore, the circulation index and level of urbanization also influence these variations [42]. The Qinghai–Tibet Plateau represents the upper limit of farming and multiple cropping. However, with increasing temperatures, the cultivated land area and upper limit of the altitude suitable for crop growth on the Qinghai–Tibet Plateau have increased [5,43,44]. Qinghai is located in the northeastern part of the Qinghai–Tibet Plateau, where altitude is the key factor influencing the FFD, LFD, and FFP. Owing to the pronounced terrain fluctuations in Qinghai, temperature varies significantly with increasing

altitude. The second most influential factor is longitude, which spans a wide range (89–104° E). In contrast, the latitude range is small (31–40° N), resulting in only a minor effect on the FFD, LFD, and FFP. With the development of a warmer and more humid climate, the crop production potential of the Qinghai Plateau is expected to improve. Consequently, the planting range of plateau crops will expand to high latitudes, and the distribution of suitable planting areas will shift accordingly.

Qinghai Province spans an elevation range from approximately 1620 m in the east to about 6830 m in the west, providing a natural experimental setting for analyzing the elevation dependence of frost variables. This study found that for every 10 m increase in elevation, the FFD advanced by 0.18 days, the LFD was delayed by 0.32 days, and the FFP shortened by 0.5 days—an elevation gradient effect that is rarely observable in low-altitude regions nationwide. From the low-altitude Eastern Agricultural Zone to the high-altitude Sanjiangyuan and Qilian Mountains, the FFP differs by nearly 70 days, and this substantial spatial variation is predominantly controlled by elevation. Furthermore, the response rates of frost variables to climate warming vary substantially along different elevation gradients. Similar to findings in the Tibet region [40], the rate of FFP prolongation in Qinghai also increases with elevation. This elevation-dependent response may be associated with the more pronounced warming trend at higher altitudes, the feedback effects of snow cover changes on surface albedo, and vertical differences in atmospheric boundary-layer structure. In contrast, studies conducted in low-altitude regions such as the North China Plain and the Huang–Huai–Hai Plain, which have relatively flat terrain, are unable to show this important elevation gradient effect. Such elevation-dependent frost changes, however, are not unique to the Qinghai–Tibet Plateau; similar altitudinal patterns have been documented in other high-mountain regions, including the European Alps [45] and the Andes [46]. In addition, the spatiotemporal variation characteristics of the FFD, LFD, and FFP, along with the elevation gradient effects identified in this study, can provide a scientific basis for developing differentiated frost disaster prevention strategies for different crops and across different elevation zones.

An abrupt period of extreme climate events in China occurred from the 1980s to the 1990s [47], during which the FFD, LFD, and FFP each experienced distinct change points [34]. The Qinghai–Tibet Plateau experienced a sudden change from cold to warm in 1987 [48]. However, the FFD, LFD, and FFP in Qinghai Province exhibited change points in 1998, 2004, and 1999, respectively. After this change in climate state, the trends of delayed FFD, advanced LFD, and prolonged FFP became evident. These change points differ from those reported in other high-altitude regions. For instance, in the northern Rocky Mountains, the timing of such transitions may be explained by season-dependent interannual-to-interdecadal changes in atmospheric circulation associated with Pacific Ocean sea surface temperatures [47]. In the eastern monsoon region of China, which is also the major grain-producing area, frost changes are primarily controlled by factors such as the intensity of the East Asian monsoon, land–sea thermal contrast, and the subtropical high, resulting in a relatively stable climate system. In contrast, Qinghai Province is situated at the convergence of the westerlies and the Indian monsoon, two major circulation systems, rendering its climatic driving mechanisms considerably more complex. The westerlies dominate the hydroclimatic processes in the northern and western parts of Qinghai, modulating seasonal precipitation variability and the intensity of the Indian summer monsoon through westerly–monsoon interactions. Meanwhile, the thermal forcing of the plateau exerts a substantial seasonal influence on atmospheric circulation. The combined effects of these multiple circulation systems make the driving mechanisms of frost changes in Qinghai far more complex than those in the eastern monsoon region. Moreover, surface processes such as seasonal freeze–thaw dynamics, snow cover, and

surface albedo feedback respond to climate change in ways that are distinctive to plateau environments. This complex driving mechanism, resulting from the combined influences of westerly–monsoon interactions and plateau thermodynamic effects, represents a unique perspective not captured in studies conducted in low-altitude regions. It also provides important clues for understanding the differential responses of frost dynamics in high-altitude areas under global warming.

These findings provide a scientific basis for adjusting crop planting boundaries and optimizing agricultural layouts in high-altitude regions under climate change. However, this study was limited by the lack of crop-specific frost sensitivity data and future climate scenario projections. Future research should incorporate crop growth models and climate prediction data to quantitatively assess frost risk dynamics and inform adaptive agricultural strategies.

It should be acknowledged that this study has three main limitations. First, the adoption of a single 0 °C frost threshold does not capture the differential sensitivity of various crop species and growth stages to sub-zero temperatures. Second, the agricultural implications are derived solely from meteorological observations, without direct measurements of actual crop damage or yield losses. Third, the uneven distribution of weather stations across Qinghai Province may introduce spatial biases. Nevertheless, our results provide a preliminary assessment of frost regime changes and underscore the need for future integrated studies that combine climate, crop, and socio-economic data.

5. Conclusions

This study demonstrated that the FFD, LFD, and FFP in Qinghai Province occurred on 5 October, 14 May, and lasted 144 days, respectively. The FFD, LFD, and FFP in Qinghai Province and each region showed significant delay, advance, and extension trends, respectively, reflecting climate warming in Qinghai. From low to high altitudes, the FFD, LFD, and FFP gradually advanced, delayed, and shortened, respectively. Lower (higher) altitudes were associated with earlier (later) FFDs, later (earlier) LFDs, and longer (shorter) FFPs. Specifically, the FFD, LFD, and FFP in the Three-River Source Area and Qilian Mountain areas occurred earlier and later, respectively, and were shorter than those in the Qaidam Basin and the Eastern Agricultural Area. Over the past 63 years, the 51 meteorological stations in Qinghai recorded delays in the FFD, advances in the LFD, and extensions in the FFP. The FFD, LFD, and FFP in Qinghai Province experienced change points in 1998, 2004, and 1999, respectively. Following these change points, the FFD, LFD, and FFP showed significant delay, advance, and extension trends, respectively.

These findings inform adaptive agricultural strategies in high-altitude regions, though future research should integrate crop growth models with climate projections to address the current limitations in crop-specific frost sensitivity data and quantitative risk assessment.

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Abbreviations

The following abbreviations are used in this manuscript:

FFD	First frost date
FFP	Frost-free period
LFD	Last frost date

References

1. Ma, S.Q.; Zhang, B.; Yang, W.Y.; Yang, M.; Wei, K.; Li, S.; He, H.; Hou, Q.; Wei, H.D. Spatial and temporal changes of the abnormal first and last frosts and their influencing factors in Huaihe River Basin from 1960 to 2015. *J. Nat. Resour.* **2019**, *34*, 359–373. [\[CrossRef\]](#)
2. Wang, G.; Xu, Y.; Zhu, Y.; Zhang, H.; Liao, J. The spatial and temporal characteristics and trend of frost days over China for the past 50 years. *Meteorol. Mon.* **2009**, *35*, 61–67. [\[CrossRef\]](#)
3. Ma, S.Q.; Zhang, B.; Tang, M.; Ma, B.; Yang, M.; Liang, J.J.; Zhang, J.Q.; Jia, L.G. Analysis on the temporal and spatial changes of frost date in the Huaihe River Basin from 1960 to 2015. *Chin. J. Agrometeorol.* **2018**, *39*, 468–478. [\[CrossRef\]](#)
4. Li, S. *Agroclimatic Resources and Agroclimatic Regionalization in China*; Science Press: Beijing, China, 1988; pp. 56–58.
5. Zhang, G.L.; Dong, J.W.; Zhou, C.P.; Xu, X.L.; Wang, M.; Ouyang, H.; Xiao, X.M. Increasing cropping intensity in response to climate warming in Tibetan Plateau, China. *Field Crops Res.* **2013**, *142*, 36–46. [\[CrossRef\]](#)
6. Zhang, Z.C.; Zhang, S.Q.; Bin, J.H.; Dou, X.Y.; Feng, Z.M. Analysis of fine spatial-temporal variation of agroclimatic heat resource in Urumqi-Changji Region of Xinjiang. *Chin. J. Agrometeorol.* **2011**, *32*, 598–606. [\[CrossRef\]](#)
7. IPCC. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Summary for Policymakers Climate Change. In *The Physical Science Basis*; Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Eds.; Cambridge University Press: Cambridge, UK, 2021; pp. 3–32.
8. Meehl, G.A.; Tebaldi, C.; Nychka, D. Changes in frost days in simulations of twenty-first century climate in simulations of twenty first century climate. *Clim. Dyn.* **2004**, *23*, 495–511. [\[CrossRef\]](#)
9. Han, R.Q.; Li, W.J.; Ai, W.X.; Song, Y.L.; Ye, D.X.; Hou, W. The climatic variability and influence of first frost Dates in Northern China. *Acta Geogr. Sin.* **2010**, *65*, 525–532. [\[CrossRef\]](#)
10. Cai, F.; Ming, H.Q.; Ji, R.P.; Zhang, S.J.; Feng, R.; Wu, J.W.; Zhang, Y.S.; Wang, Y. Spatiotemporal evolution characteristics of frost-free period in the past 50 years in Liaoning. *Chin. J. Agrometeorol.* **2010**, *31*, 188–193. [\[CrossRef\]](#)
11. Fan, X.H.; Wang, Q.X.; Wang, M.B. Study on the characteristics of the frost-free period in Shanxi Province in the past 50 years. *Ecol. Environ. Sci.* **2010**, *19*, 2393–2397. [\[CrossRef\]](#)
12. Zhao, S.W.; Ji, R.P.; Yu, W.Y.; Zhao, S.Y.; Zhang, Y.S. Interdecadal variation of late spring frost and the relationship with SST in Liaoning. *Desert Oasis Meteorol.* **2023**, *17*, 65–73. [\[CrossRef\]](#)
13. Lin, J.J.; Guo, H. Analysis of the characteristics of frost changes in Pingliang from 1971 to 2012. *Desert Oasis Meteorol.* **2015**, *9*, 57–62. [\[CrossRef\]](#)
14. Xu, F.X.; Zhang, S.; Wang, Q.Z.; Chang, C.; Qin, Y.P. Characteristics of change in first, last-frost day and frost-free season in Shouguang from 1961 to 2015 and its impact on agriculture. *Chin. Agric. Sci. Bull.* **2019**, *35*, 112–117. [\[CrossRef\]](#)
15. Bonsal, B.R.; Zhang, X.; Vincent, L.A.; Hogg, W.D. Characteristics of daily and extreme temperatures over Canada. *J. Clim.* **2001**, *14*, 1959–1976. [\[CrossRef\]](#)
16. Heino, R.; Brázdil, R.; Førland, E.; Tuomenvirta, H.; Alexandersson, H.; Beniston, M.; Pfister, C.; Rebetez, M.; Rosenhagen, G.; Rösner, S.; et al. Progress in the study of climatic extremes in Northern and Central Europe. *Clim. Change* **1999**, *42*, 151–181. [\[CrossRef\]](#)
17. Anandhi, A.; Zion, M.S.; Gowda, P.H.; Pierson, D.C.; Lounsbury, D.; Frei, A. Past and future changes in frost day indices in Catskill Mountain region of New York. *Hydrol. Processes* **2013**, *27*, 3094–3104. [\[CrossRef\]](#)

18. Erlat, E.; Türkeş, M. Analysis of observed variability and trends in numbers of frost days in Turkey for the period 1950–2010. *Int. J. Clim.* **2012**, *32*, 1889–1898. [\[CrossRef\]](#)
19. Easterling, D.R. Recent changes in frost days and the frost-free season in the United States. *Bull. Am. Meteorol. Soc.* **2002**, *83*, 1327–1332. [\[CrossRef\]](#)
20. Zhai, P.M.; Pan, X.H. Trends in temperature extremes during 1951–1999 in China. *Geophys. Res. Lett.* **2003**, *30*, 17. [\[CrossRef\]](#)
21. Ning, X.J.; Zhang, L.J.; Yang, Q.T.; Qin, Y.C. Trends in the frost-free period in China from 1951 to 2012. *Acta Geogr. Sin.* **2015**, *70*, 1811–1822. [\[CrossRef\]](#)
22. Qian, W.H.; Lin, X. Regional trends in recent temperature indices in China. *Clim. Res.* **2004**, *27*, 119–134. [\[CrossRef\]](#)
23. Ren, J.Q.; Guo, C.M.; Wang, L.W.; Li, J.P.; Liu, Y.X.; Li, Q. Spatial and temporal distribution characteristics and impact factors of the frost over Jilin Province from 1961 to 2015. *J. Meteorol. Environ.* **2018**, *34*, 119–125. [\[CrossRef\]](#)
24. Cheng, Y.; Wu, J.; Li, H.; Huang, W.B.; Wang, X.W. The variation characteristics of frost in Gansu Province from 1961 to 2017 and its impact on agriculture. *J. Nat. Disasters* **2019**, *28*, 37–46. [\[CrossRef\]](#)
25. Guo, J.W.; Shan, H.T.; Guo, J.T. Characteristics of spatiotemporal distribution and variation of frost in semiarid regions of the Loess Plateau in central Gansu. *Res. Soil Water Conserv.* **2020**, *27*, 101–105. [\[CrossRef\]](#)
26. Duan, J.; Wang, W.T.; Xu, Y.; Ru, Y.X. Evolution and driving factors of grain supply and demand balance in the Qinghai–Tibet Plateau in recent 30 years. *Acta Ecol. Sin.* **2024**, *44*, 10411–10426. [\[CrossRef\]](#)
27. Yue, S.; Pilon, P.; Phinney, B.; Cavadias, G. The influence of autocorrelation on the ability to detect trend in hydrological series. *Hydrol. Processes* **2002**, *16*, 1807–1829. [\[CrossRef\]](#)
28. Tian, X.; Sa, C.L.; Meng, F.H.; Luo, M.; Wang, M.L.; Zhang, X.; Zhang, H.C. Analysis of spatiotemporal evolution characteristics of freeze–thaw state of surface soil in Inner Mongolia over the past 40 years. *Res. Soil Water Conserv.* **2025**, *32*, 148–159. [\[CrossRef\]](#)
29. Goossens, C.; Berger, A. Annual and seasonal climatic variations over the Northern Hemisphere and Europe during the last century. *Ann. Geophys.* **1986**, *4*, 385–400. [\[CrossRef\]](#)
30. Yue, S.; Wang, C. The Mann–Kendall test modified by effective sample size to detect trend in serially correlated hydrological series. *Water Resour. Manag.* **2004**, *18*, 201–218. [\[CrossRef\]](#)
31. Pettitt, A.N. A non-parametric approach to the change-point problem. *Appl. Stat.* **1979**, *28*, 126–135. [\[CrossRef\]](#) [\[PubMed\]](#)
32. Jiang, X.; Xu, J.; Pan, L.J.; Chen, N.; Wang, T.; Jiang, X.D.; Yin, X.Z.; Yang, Z.; Yu, S.L.; Chi, X.Y. Peanut yield-related traits and meteorological factors correlation analysis in multiple environments. *Acta Agron. Sin.* **2023**, *49*, 3110–3121. [\[CrossRef\]](#)
33. Ma, Q. *The Temporal and Spatial Distribution of Frost and Hazard Risk of Winter Wheat Late Freezing in the Loess Plateau from 1980 to 2014*; Northwest Normal University: Lanzhou, China, 2016. [\[CrossRef\]](#)
34. Zhang, Z.G.; Xu, X.M.; Guo, C.F.; Cai, M.T.; Yuan, Z.; Zhang, M.Z. Spatial and temporal characteristics and influencing factors of frost date in the Yellow River Basin from 1960 to 2020. *Arid Land Geogr.* **2022**, *45*, 1685–1694. [\[CrossRef\]](#)
35. Jiao, W.; Zhang, B.; Ma, B.; Cui, Y.; Xing, L.; Wang, X.; Hunag, H. Variation characteristics of the date of first frost and last frost and the frost-free period in North China in recent 58 years. *Plateau Meteorol.* **2021**, *40*, 343–352. [\[CrossRef\]](#)
36. Zhang, X.; Lou, J.W.; Wang, Y.; Wang, Z.K. Temporal and spatial variation characteristics of first and last frost day and frost period from 1961 to 2017 in northern Xinjiang. *Arid Land Geogr.* **2021**, *44*, 308–315. [\[CrossRef\]](#)
37. Bai, L.; Zhang, F.; Wen, Y.; Shi, C.X.; Wu, J.; Shang, M.; Zhu, Z.; Meng, J.Y. Evolution of the frost hazards based on gridded meteorological data across China in 1961–2018. *Chin. J. Agrometeorol.* **2021**, *42*, 761–774. [\[CrossRef\]](#)
38. Li, F.; Zhang, J.X. Regional characteristics of the first frost over Shanxi province in latest 5 decades. *J. Catastrophology* **2013**, *28*, 104–109, 181. [\[CrossRef\]](#)
39. Zhou, X.Y.; Zhao, C.Y.; Cui, Y.; Liu, M.Y.; Ao, X.; Yi, X.; Hou, Y.L.; Zhang, X.Y. Variation characteristics of the date of first frost and last frost and the frost-free period in the Northeast China during 1961–2013. *J. Nat. Resour.* **2017**, *32*, 494–506. [\[CrossRef\]](#)
40. Li, C.Y.; Guo, Y.N.; Du, J.; So, N.; Wang, T. Spatial and temporal distribution of the first frost date, last frost date and the frost-free period in Tibet from 1981 to 2020. *Plateau Mt. Meteorol. Res.* **2024**, *44*, 78–84. [\[CrossRef\]](#)
41. Chen, Q.; Zhang, Y. Study on climatic features of unusual first and last frost in North China. *J. Nat. Disasters* **1995**, *4*, 33–39. [\[CrossRef\]](#)
42. Jia, Y.Q.; Zhang, B.; Zhang, Y.Z.; Tang, M.; Ma, B.; Wang, G.Q.; Liu, X.L.; Luo, Z.M. Effect of urbanization on spatial and temporal variation of extreme temperature events in the Yangtze River delta. *J. Nat. Resour.* **2017**, *32*, 814–828. [\[CrossRef\]](#)
43. Peng, J.; Liu, Z.H.; Liu, Y.H.; Wu, J.S.; Han, Y.N. Trend analysis of vegetation dynamics in Qinghai–Tibet plateau using Hurst exponent. *Ecol. Indic.* **2012**, *14*, 28–39. [\[CrossRef\]](#)
44. Ma, W.D.; Su, P.; Jia, W.; Liu, F.G.; Wang, J.A. Advances in the research on the exposure of highland barley natural disasters on the background of climate change. *J. Catastrophology* **2020**, *35*, 215–221. [\[CrossRef\]](#)
45. Kuhn, M.; Olefs, M. Elevation-dependent climate change in the European Alps. In *Oxford Research Encyclopedia of Climate Science*; von Storch, H., Ed.; Oxford University Press: New York, NY, USA, 2020. [\[CrossRef\]](#)
46. Pabón-Caicedo, J.D.; Arias, P.A.; Carril, A.F.; Espinoza, J.C.; Borrel, L.F.; Goubanova, K.; Lavado-Casimiro, W.; Masiokas, M.; Solman, S.; Villalba, R. Observed and projected hydroclimate changes in the Andes. *Front. Earth Sci.* **2020**, *8*, 61. [\[CrossRef\]](#)

47. Zhang, D.R.; Zheng, J.; Fan, J.L.; Fang, Z.C.; Ji, Q.Y.; Yuan, Y.Z.; Liu, W.F. Spatiotemporal variations of extreme temperature indices in different climatic zones of China over the past 60 years. *Chin. J. Agrometeorol.* **2019**, *40*, 422–434. [[CrossRef](#)]
48. Li, L.; Chen, X.G.; Wang, Z.Y.; Xu, W.X.; Tang, H.Y. Climate change and its regional differences over the Tibetan Plateau. *Adv. Clim. Change Res.* **2010**, *6*, 181–186. [[CrossRef](#)]

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