Climatic Evolution of First Frost Dates in Ningxia Based on Ground Temperature and Causes of Circulation Anomalies: Postprint

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Abstract

Using surface temperature data from 20 meteorological stations in Ningxia since 1961 and monthly geopotential height field data from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR), this study investigates the latest climate evolution characteristics of the first frost date in Ningxia and its associated circulation anomalies, providing theoretical support for frost disaster prediction efforts in the region. The results show that: (1) The first frost date in Ningxia exhibits a spatial distribution pattern of "earlier in the south and later in the north," occurring earliest in the Loess Hilly Region, followed by the Central Arid Zone, and latest in the Yellow River Irrigation Area, which is consistent with the distribution pattern of daily average minimum temperature showing "lower in the south and higher in the north." (2) The first frost date in Ningxia shows significant differences before and after the period of pronounced global warming. Compared to the climatological mean (1981–2010), the first frost date was generally earlier in the pre-warming period (1961–1980), occurring on average in late September with an average advance of 7 days across the region; in the post-warming period (1981–2019), it was significantly later, occurring on average in early October with an average delay of 2 days across the region, and even later by an average of 5 days after 2000. (3) Since 1961, the first frost date in Ningxia has been significantly delayed at a rate of 3.0 d · (10a)-1, with the most pronounced trend in the Yellow River Irrigation Area reaching 3.2 d · (10a)-1, followed by the Central Arid Zone and Loess Hilly Region at 2.6 d · (10a)-1 and 2.7 d · (10a)-1, respectively; however, exceptionally early first frost events still occur against the background of climate warming, with probabilities of early occurrence since the new century being 15%, 25%, and 30% for the Yellow River Irrigation Area, Central Arid Zone, and Loess Hilly Region, respectively. (4) The high-, middle-, and low-level atmospheric circulations in years with early and late first frost dates in Ningxia exhibit significant interdecadal and interannual differences,

with distinctly opposite spatial distributions. When the first frost date is earlier (later) than normal, the East Asian trough is stronger (weaker) than usual and the Western Pacific subtropical high is weaker (stronger) than usual, which is conducive (unfavorable) to the active southward movement of cold air.

Full Text

Climate Change Characteristics and Circulation Anomaly Causes of the First Frost Date in Ningxia Based on Ground Temperature

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Abstract: Based on ground temperature data from 20 meteorological stations in Ningxia since 1961 and monthly geopotential height field data from NCEP/NCAR, this study investigates the latest climatic evolution characteristics of the first frost date in Ningxia and the influence of circulation anomalies, providing theoretical support for frost disaster prediction. The results show that: (1) The first frost date in Ningxia exhibits a spatial distribution pattern of "earlier in the south, later in the north," with the loess hilly area earliest, the middle arid belt second, and the latest occurrence in the Yellow River irrigation area, consistent with the "lower in the south, higher in the north" pattern of daily minimum temperature. (2) Significant differences exist in the first frost date before and after pronounced global warming. Compared with the climatic mean, the pre-warming period (1961–1980) was generally earlier, occurring in late September on average, while the post-warming period (1981–2019) was notably later, occurring in early October on average. (3) Since 1961, the first frost date in Ningxia has been significantly delayed, with a trend of 3.0 d · $(10a)^{-1}$, most pronounced in the Yellow River irrigation area at 3.2 d · $(10a)^{-1}$, followed by the middle arid belt and loess hilly area at 2.6 d · $(10a)^{-1}$ and 2.7 d · $(10a)^{-1}$ respectively. However, abnormally early first frost still occurs under climate warming, with probabilities of 15%, 25%, and 30% since 2000 in the three regions. (4) Significant interdecadal and interannual differences exist in the high-, middle-, and low-level atmospheric circulations between early and late first frost years, with opposite spatial distributions. When the first frost date is earlier (later), the East Asian trough is stronger (weaker) than normal, the Siberian high is stronger (weaker), and the Western Pacific subtropical high is weaker (stronger), favoring (inhibiting) active southward movement of cold air.

Keywords: first frost date; climate evolution characteristics; linear trend; atmospheric circulation anomaly

1 Introduction

Frost refers to a common agrometeorological disaster where air temperature near the soil or plant canopy drops below 0°C for a short period, causing water in plants to freeze, cells to rupture, and resulting in plant injury, death, yield reduction, or complete crop failure. Annual agricultural economic losses from frost in China can reach hundreds of millions of yuan. The first frost marks the initial occurrence of frost during the transition from warm to cold seasons. Its timing—whether early or late—determines the degree of freeze damage to crops, affecting grain maturity and potentially causing substantial yield losses or complete crop failure. Located in the inland northwest, Ningxia features complex and diverse climate conditions. Despite its unique geographical, climatic, and soil advantages that have made it a high-quality crop production base, Ningxia also experiences the highest frequency and most severe frost damage in China. For instance, the first frost in 1999 caused severe freeze damage to thousands of hectares of crops, while in 2003, frost in Jingyuan and Xiji severely affected grape harvesting. Therefore, analyzing the first frost date in Ningxia is essential for comprehensive understanding of regional climate change and disaster prevention.

Under global climate warming, different regions in China respond differently to global warming, with various extreme climate events increasing and frost risk to plants changing accordingly. Closely linked to temperature changes and significantly impacting crops, the first frost date must exhibit new climatic evolution characteristics worth further investigation. Consequently, numerous scholars have conducted extensive research on first frost dates and their influencing factors across China. Regarding spatial distribution, Chen et al. studied climate change characteristics of first frost in Northwest China using daily minimum temperature, finding earliest occurrence on the Qinghai Plateau, followed by the southern Xinjiang basin, and latest in Longnan-southern Shaanxi, with a significant delay since 1978. Ye et al. analyzed first frost changes across China from 1961–2007 using data from 743 stations, showing significant delay since the 1980s. Shen et al. examined first frost in the Sanjiang Plain, revealing a "two-peak, two-valley" spatial distribution pattern and a delay trend possibly correlated with global warming greenhouse effects. These studies demonstrate regional differences in spatial distribution but consistent temporal delays under climate warming.

What causes the timing of first frost dates? Research shows that first frost timing in Heilongjiang is influenced by the Eurasian meridional circulation pattern, Okhotsk Sea high, Aleutian low, East Asian trough intensity, and Western Pacific subtropical high. Li et al. identified cold air strength, subtropical high, and topography as fundamental factors affecting frost zoning. Li et al. revealed close correlation between first frost dates north of the Yangtze River and the Arctic Oscillation (AO) index. Gao found that mid-latitude circulation systems play important roles in first frost timing in Inner Mongolia, primarily controlled by 500 hPa low pressure.

As one of China's most frost-affected regions, Ningxia has seen relevant research. Li et al. analyzed and evaluated late frost disaster risk using ArcGIS. Zhang et al. monitored different frost types using NOAA satellite data. However, few studies analyze climate characteristics and circulation anomaly causes of first frost dates in Ningxia, with most defining first frost based on daily minimum air temperature. Han et al. demonstrated that ground temperature-defined first frost dates better match reality and benefit prediction operations. Therefore, this study uses ground temperature to define first frost dates, analyzing new climate evolution characteristics and exploring circulation anomaly causes to provide theoretical support for frost disaster prediction and improve disaster prevention capabilities.

1.1 Study Area Overview

Ningxia is located in inland China, far from the ocean, with coordinates of 104°17 ~109°39 E and 35°14 ~39°23 N. The terrain is complex, with elevations above 1000 m, gradually sloping from southwest to northeast. The topography descends stepwise from high south to low north, with a drop of nearly 1000 m, representing typical continental climate with insufficient moisture sources. Annual average precipitation is 283.0 mm, unevenly distributed. Based on climate conditions, agricultural distribution, ecological environment, and traditional practices, Ningxia is commonly divided into three regions: the Yellow River irrigation area, middle arid belt, and loess hilly area (Fig. 1), which this study adopts.

1.2 Data

Considering station establishment time and geographical distribution, 20 meteorological stations in Ningxia were selected (Fig. 1). Data include daily ground temperature (0 cm) and daily minimum temperature from these stations, plus NCEP/NCAR reanalysis data with 2.5°$×$2.5° grid resolution, including monthly geopotential height fields and sea level pressure. The climatic mean is defined as 1981–2010. Since temperature is the direct factor affecting frost, to explore its relationship with air temperature, Fig. 2 shows the average daily minimum temperature in early October (when frost commonly occurs). The spatial distribution of "lower south, higher north" aligns with the "earlier south, later north" pattern of first frost dates.

1.3 Methods

According to the meteorological industry standard of the People' s Republic of China (QX/T 88-2008), the first frost date is defined as the first date when daily ground temperature at a meteorological observation station falls below 0°C during the transition from warm to cold seasons. For calculation convenience, dates are numbered sequentially from January 1 (day 1, 2, 3,⋯) to establish a dataset for analysis. Linear trend analysis and other common meteorological statistical methods are used to analyze spatial distribution and interannual/decadal evolution characteristics of first frost dates. Correlation analysis and composite analysis methods are employed to investigate atmospheric circulation anomaly causes affecting first frost dates.

2 Climate Change Characteristics of First Frost Date

2.1 Average Spatial Distribution Characteristics

The average first frost date in Ningxia is early October, showing a "southern early, northern late" spatial pattern. Frost appears earliest in the high-altitude loess hilly area (late September on average), followed by the middle arid belt (early October), and latest in the Yellow River irrigation area (early October). Longde in the loess hilly area is earliest (September 26), while Tongxin in the middle arid belt and Shizuishan, Helan, and Wuzhong in the irrigation area are latest (October 13). The spatial distribution pattern is consistent with the "southern low, northern high" distribution of daily minimum temperature (Fig. 2).

2.2 Spatial Distribution Characteristics Before and After Climate Warming

Since the 1980s, global climate has warmed significantly. Studies show Ningxia experienced climate jumps in the late 1980s and mid-1990s. Using 1981 as the boundary, significant differences emerge in first frost dates before and after warming. Compared with the climatic mean (1981–2010), pre-warming (1961–1980) first frost dates were generally earlier, occurring in late September, averaging 5 days earlier across the region. Post-warming (1981–2019), dates were notably later, occurring in early October, averaging 2 days later, and 5 days later after 2000. The spatial distribution of "southern early, northern late" remained consistent before and after warming, but with substantial temporal differences (Fig. 3). Pre-warming, first frost occurred in late September (early October only at Yinchuan, Helan, Lingwu, Wuzhong, Zhongwei, and Tongxin), 5 days earlier than the climatic mean. Post-warming, the loess hilly area experienced frost in late September, while the middle arid belt and irrigation area saw frost in early October, 2 days later than the climatic mean. Compared with pre-warming, post-warming dates were delayed by 7 days regionally, with the irrigation area and middle arid belt delayed by about 8 days and the loess hilly area by about 5 days.

2.3 Interannual Variation Characteristics

Compared with using daily minimum temperature as the frost standard, using 0 cm ground temperature shows no difference in spatial distribution but reveals interannual variation differences. Both standards show delaying trends, but the ground temperature trend is larger and dates are generally later. Compared with actual frost dates in the *China Disaster Dictionary (Ningxia Volume)*, ground temperature-defined dates are more realistic. For example, on September 23, 1972, frost occurred in Guyuan, Xiji, Haiyuan, Longde, Tongxin, Yanchi, Zhongwei, Helan, and Pingluo—ground temperature criteria matched reality at all locations except Longde, while air temperature criteria only matched at Jingyuan.

Further analysis of extreme values shows earliest first frost typically occurs in early-mid September during pre-warming years, with HuiNong, Taole, Qingtongxia, Zhongning, Yanchi, Haiyuan, Tongxin, Guyuan, and Xiji all experiencing frost before September 23. Latest frost occurs in late October to early November during post-2000 years, particularly in mid-late October. All stations except Longde experienced latest frost after 2000, with HuiNong, Lingwu, Zhongwei, Zhongning, Yanchi, Tongxin, Xiji, Guyuan, and Longde latest in mid-late October, and Taole, Qingtongxia, and Yongning latest in early November. This may relate to significantly above-normal temperatures in those years (2000 and 2006 ranked 1st and 2nd historically). When temperatures are abnormally high, first frost dates are generally later.

The long-term linear trend shows Ningxia' s first frost date has significantly delayed at 3.0 $\mathrm{d \cdot (10a)^{-1}}$, exceeding the 0.001 significance level. All three regions show significant delaying trends: irrigation area most prominent at 3.2 $\mathrm{d \cdot (10a)^{-1}}$, middle arid belt at 2.6 $\mathrm{d \cdot (10a)^{-1}}$, and loess hilly area at 2.7 $\mathrm{d \cdot (10a)^{-1}}$, all exceeding 0.001 significance. Despite this significant delay, especially under recent climate warming, abnormally early frost still occurs, with probabilities of 15%, 25%, and 30% since 2000 in the irrigation area, middle arid belt, and loess hilly area respectively (Fig. 5).

3 Atmospheric Circulation Anomaly Causes

Atmospheric circulation critically affects climate change. High-level tropospheric energy can propagate downward, influencing mid-lower tropospheric circulation and energy distribution, with circulation anomalies often serving as precursor signals for important weather processes. Since the regional average first frost date occurs in early October, October is considered the concurrent period and months before October the pre-frost period for discussing circulation causes.

3.1 Interdecadal Differences in Atmospheric Circulation Before and After Warming

Significant differences exist in first frost dates before and after warming (Fig. 3). Global atmospheric circulation also underwent significant interdecadal changes around 1981. Using 1981 as the boundary, we compare circulation differences between pre-warming (generally early frost) and post-warming (generally late frost) periods. Post-warming, the 200 hPa, 500 hPa, and surface levels are dominated by positive anomalies with inactive cold air, while pre-warming shows the opposite pattern with negative anomalies and active cold air (Fig. 6).

Specifically, post-warming October sea level pressure shows large positive anomalies in high-latitude areas north of 60°N, with the Okhotsk Sea as a clear negative anomaly center. China lies under positive anomaly control with a weakened East Asian trough and stronger Western Pacific subtropical high, inhibiting cooling. Pre-warming patterns are opposite, with negative anomalies across all levels, a deeper East Asian trough, and weaker subtropical high, favoring active southward cold air movement.

Difference analysis reveals significant circulation differences from high to surface levels between periods, showing a "+ - +" anomaly pattern at 200 hPa, 500 hPa, and surface, with anomaly centers corresponding to those in pre/post-warming periods, mostly passing 0.001 significance levels (Fig. 6).

3.2 Atmospheric Circulation Anomalies in Typical Early/Late Years After Warming

To predict frost trends under climate warming, we selected the top 5 late years (1984, 1991, 1999, 2006, 2017) and top 5 early years (1962, 1967, 1972, 1978, 1980) from the 1981–2019 sequence for composite analysis of circulation anomalies.

In late years, 200 hPa, 500 hPa, and surface levels form a "+ - +" anomaly wave train across Eurasian mid-high latitudes. At 200 hPa, mid-high latitudes show positive anomalies with a two-ridge-one-trough pattern (ridges over western Europe and Mongolia, trough over the Ural Mountains). China is under positive anomaly control with a weaker East Asian trough and stronger Western Pacific subtropical high, inhibiting cooling (Fig. 7). At 500 hPa, a "+ - +" wave train appears with a ridge over the East European plain, trough from Balkhash Lake to Baikal Lake, and ridge near Japan Sea. The subtropical high is stronger, the East Asian trough shallower, and cold air inactive. At surface, a "+ - +" wave train shows a small high-pressure center near 100°E and negative anomalies in Japan Sea, with a strong thermal low and weak Siberian high over China, unfavorable for cooling and resulting in later frost dates.

In early years, 200 hPa, 500 hPa, and surface levels form an opposite "- + -" anomaly wave train. At 200 hPa, mid-high latitudes show negative anomalies with a two-trough-one-ridge pattern (troughs over East European plain and eastern Inner Mongolia, ridge north of Balkhash Lake), favoring cold air southward movement (Fig. 7). At 500 hPa, a "- + -" wave train shows a trough over Europe, ridge from Balkhash Lake to Baikal Lake, and deep trough near Japan Sea. The subtropical high is weaker and more southward, the East Asian trough deeper, and cold air more active. At surface, a "- + -" wave train shows a negative center near 100°E, with a weak thermal low over China, favoring lower temperatures and earlier frost dates.

In summary, post-warming circulation anomalies from high to surface levels significantly affect first frost dates by constraining cold air activity. When the East Asian trough is stronger (weaker) and the Western Pacific subtropical high is weaker (stronger), cold air is more (less) active, resulting in earlier (later) first frost dates.

4 Conclusions

(1) The first frost date in Ningxia shows a "southern early, northern late" spatial pattern, earliest in the loess hilly area, followed by the middle arid belt, and latest in the Yellow River irrigation area. Tongxin in the middle arid belt and Shizuishan, Helan, and Wuzhong in the irrigation area are among the latest, while Longde is earliest. This pattern aligns with the "southern low, northern high" distribution of daily minimum temperature.

(2) Significant differences exist before and after pronounced global warming. Compared with the climatic mean, pre-warming (1961–1980) first frost was generally earlier in late September (5 days early), while post-warming (1981–2019) was later in early October (2 days late, 5 days late after 2000). Compared with pre-warming, post-warming dates delayed by 7 days regionally, with irrigation area and middle arid belt delayed by about 8 days and loess hilly area by about 5 days.

(3) Extreme analysis shows earliest first frost typically occurred in early-mid September during pre-warming years, while latest frost occurred in late October-early November during post-2000 years. The long-term trend shows significant delay of 3.0 d $\cdot$ $(10a)^{-1}$ regionally, with irrigation area at 3.2 d $\cdot$ $(10a)^{-1}$, middle arid belt at 2.6 d $\cdot$ $(10a)^{-1}$, and loess hilly area at 2.7 d $\cdot$ $(10a)^{-1}$, all exceeding 0.001 significance. Despite significant delay, abnormally early frost still occurs, with probabilities of 15%, 25%, and 30% since 2000 in the three regions.

(4) Significant interdecadal differences exist in high-, middle-, and low-level atmospheric circulation before and after warming. Post-warming levels are dominated by positive anomalies with inactive cold air, while pre-warming shows opposite negative anomalies with active cold air. Under climate warming, typical early and late years show significantly different interannual circulation anomalies: early years feature a "- + -" wave train across Eurasian mid-high latitudes with stronger East Asian trough, active

cold air, and weaker subtropical high, favoring cooling; late years show the opposite pattern.

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