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Analysis of spatial and temporal variation of frost dates in Jilin Province

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Abstract. In order to understand the changing law of frost date (number) in Jilin Province, and to improve the early warning and forecasting ability of frost disaster, Based on the day-by-day minimum temperature data from 47 meteorological observation stations in Jilin region from 1969 to 2020, the spatial and temporal distribution characteristics of frost date (number) were analyzed by using linear propensity ratio, Mann-Kendall method and sliding t-test, as well as REOF. The results show that: the first frost date, the last frost date, and the number of frost-free days follow the general spatial distribution pattern of "early in the northwest and late in the southeast," "late in the southeast and early in the northwest," and "long in the northwest and short in the southeast". The overall trend of frost dates is delayed first frost date, and early final frost date and prolonged frost-free days. The years with abrupt changes in the first frost date, final frost date and number of frost-free days were 2004, 1997 and 1991, respectively. The number of frost-free days in Jilin Province was categorized into 3 regions based on REOF analysis. It can be seen that analyzing the spatio-temporal variation rule of frost can provide theoretical basis for frost prevention and disaster reduction.

Keywords: Jilin Province; First and last frost date; Number of frost-free days; Temporal and spatial variations; Hurst exponent.

1. Introduction

Frost refers to an agricultural meteorological disaster where plants are damaged due to temperatures dropping below 0°C during the growing season, typically occurring in spring and autumn. The date of the last frost in spring is referred to as the last frost date, while the first occurrence of frost in autumn is known as the first frost date. The days between the last frost date and the first frost date are referred to as the frost-free period [1-3]. From 1901 to 2018, there has been a global warming trend with an average temperature increase of 0.85°C. China has experienced a significant increase in temperature [4]. The rising temperatures have had an impact on the spatial and temporal distribution of frost disasters, resulting in changes in the first and last frost dates as well as an extension of the frost-free period [5−6]. Against the backdrop of global climate warming, extreme temperature fluctuations have affected the frost periods of many countries, such as the United States, Germany, and Canada [7-10]. These regions have observed a delay in the first frost date, an earlier last frost date, and a lengthening of the frost-free period. Within China, many scholars have studied the changes in the first and last frost dates, as well as the frost-free period. It has been observed that in many regions, among them, Pan Shukun, Ci H and others [11-13] used linear trend and statistical analysis to study the frost period in Xinjiang, and obtained that the first frost date was delayed, the final frost date was earlier, and the frost-free period was extended. Ye Dianxiu and others [14] concluded that the national average final frost date has been significantly earlier since the 1980s, and the first frost date has been significantly delayed since the 1990s. Wang L, Mu Chenying and others [15-16] analyzed the spatial and temporal characteristics of the first and last frost days and frost-free period in Northeast China, and concluded that the trend of frost change as a whole is conducive to the prolongation of the growing season of crops . Ma Shangqian and others [17] studied the pattern of change of frost dates in Gansu Province, in the future, the first frost date continues to be delayed, the final frost date continues to advance, and the frost-free period continues to be extended.

The province of Jilin is located in northeastern China, where frost dates have also undergone spatial and temporal changes in the context of climate warming. Previous studies by Li Ling, Qiu Yixuan, and others [18-19] have mainly focused on the risk assessment and zoning of frost-related disasters in Jilin Province. Jilin frost-free period indices, frost process evaluation criteria, and climate recurrence period indices have been established by Ji Lingling and others [20-21] specifically for spring and autumn frost in Jilin Province. However, there has been no analysis of the spatial and temporal distribution characteristics and change trends of the beginning and last frost dates, as well as the frost-free period. In this study, daily minimum temperature data from 47 meteorological observation stations in Jilin Province from 1969 to 2020 will be analyzed to investigate the spatial and temporal variation characteristics of the first and last frost dates, as well as the frost-free period. The findings will provide a scientific basis for adopting effective measures to combat frost-related disasters and enhance the ability to respond to frost-related emergencies in the face of climate change.

2. Data and Methods

2.1 Data

For this study, daily minimum temperature data spanning 52 years from 1969 to 2020 were gathered from a total of 47 meteorological observation stations in Jilin Province. The data was obtained from the Jilin Provincial Information Center. Frost is a natural disaster that occurs when temperatures drop, resulting in crop damage. In this study, frost was defined as daily minimum temperatures of ≤0°C. The first day of autumn with a daily minimum temperature of ≤0°C was considered as the first frost date, while the last day of spring with a daily minimum temperature of ≤0°C marked as the last frost date. The duration between the day following the last frost date and the day before the first frost date was defined as the frost-free period [16,22-23].

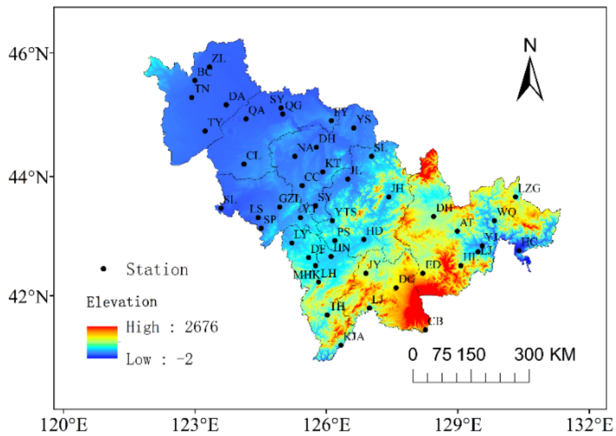


Fig.1 The distribution of meteorological observation stations in Jilin Province

2.2 Methods

2.2.1 Mann-Kendall test and moving t-test

When performing the Mann-Kendall test to detect abrupt changes in a sequence, it is done by constructing a rank series as follows:

$$S_k = \sum_{i=1}^{k} \sum_{j}^{i-1} \alpha_{ij} \ (k = 2,3,4,...,n) \tag{1}$$

Where, $\alpha_{ij} = 1$ for $X_i > X_j$, and $\alpha_{ij} = 0$ for $X_i < X_j$; in which $j = 1,2,3,...,n$.

The statistical variable is defined as:

$$UF_k = \frac{[S_k - E(S_k)]}{\sqrt{Var(S_k)}} \ (k = 1,2,3,...,n) \tag{2}$$

In equation (2), $E(S_k) = k(k+1)/4$ and $Var(S_k) = k(k-1)(2k+5)/72$.

UFk follows a standard normal distribution. Given a significance level α, if |UFk|>Uα/2, it indicates a significant change in the trend of the sequence. By rearranging the time series X in reverse order and using the equation above, we calculate the values while ensuring thatUBk=-UFk, $k = n+1-k$.

In order to analyze the trend changes in the sequence X, the statistical series UFk and UBk can be examined to identify the timing and region of abrupt changes. If UFk is greater or smaller than zero, it indicates an upward or downward trend in the sequence. When UFkand UBk exceed the confidence interval, it suggests a notable upward or downward trend. If UFk and UBk intersect within the confidence interval, then the intersection corresponds to the moment of abrupt change initiation [17].

The moving t-test method examines abrupt changes by comparing the differences in means between two segments of the same sequence. This approach [17,24] treats the means of the two subsequences within the sequence as indicators of the difference in population means. If the difference in means between the two subsequences exceeds the predetermined significance level, it is considered evidence of an abrupt change in the population mean.

2.2.2 REOF Method

The REOF analysis builds upon the traditional Empirical Orthogonal Function (EOF) analysis by incorporating rotational transformations. It involves rotating the axes of each factor to a certain position, such that each variable exhibits maximum and minimum differentiation on the rotated factor axes. As a result, high loadings are concentrated on a few variables, while the rest approach zero loadings in the rotated factor matrix. The specific formula can be found in reference [25].

3. Results and Analysis

3.1 Spatial distribution characteristics of frost dates

Figure 2(a) shows the distribution of average first frost dates across the province, generally falling within September 21st to October 13rd. The earliest first frost date occurs in Erdao, while the latest first frost date occurs in Jianshi. From September 21st to September 30th, the first frost dates are mainly concentrated in the southeastern mountainous areas of Jilin and northern areas such as Luozigou in Yanbian. From October 1st to October 13th, the first frost dates are predominantly distributed in the central and western regions of Jilin, southern areas of Tonghua, and southeastern areas such as Hunchun in Yanbian. Overall, there is a clear northwest-to-southeast trend, indicating a distinct zonal distribution pattern. In most areas of the province, the majority of first frost dates fall between October 1st and October 10th, which is also the period with the highest frequency distribution observed in the histogram.

The occurrence of the last frost [Fig. 2(b)] shows a multi-year average distribution from April 20th to May 16th across the province. The earliest occurrence of the last frost is observed in Songyuan, while the latest occurs in Erdao. From April 20th to May 4th, the last frost mainly concentrates in the central and western regions of Jilin, the Tonghua area, and the southeastern part of Yanbian. The region from May 4th to May 16th is primarily distributed in the southeastern mountainous areas of Jilin, including Baishan and the western part of Yanbian. Looking at the province as a whole, the distribution of the last frost dates demonstrates a stepped pattern. Overall, it exhibits a distribution pattern of a later occurrence in the southeast and an earlier occurrence in the northwest, showcasing the same zonal distribution rule.

The distribution characteristics of frost-free days [Fig. 2(c)] are similar to those of the first frost period. Overall, the spatial distribution shows a longer duration in the northwest and a shorter duration in the southeast. The shortest period of frost-free days is observed in Erdao, with a duration of 125 days, while the longest period is found in Jilin, with a duration of 173 days, indicating a difference of 48 days between the two. The range of 125-146 days of frost-free days is mainly concentrated in the southeastern mountainous areas, possibly due to the combined influence of mountains, altitude, and geographical location. The area occupied by the range of 153-172 days is larger than that of 125-153 days. In general, the duration of frost-free days ranges from 148 to 163 days.

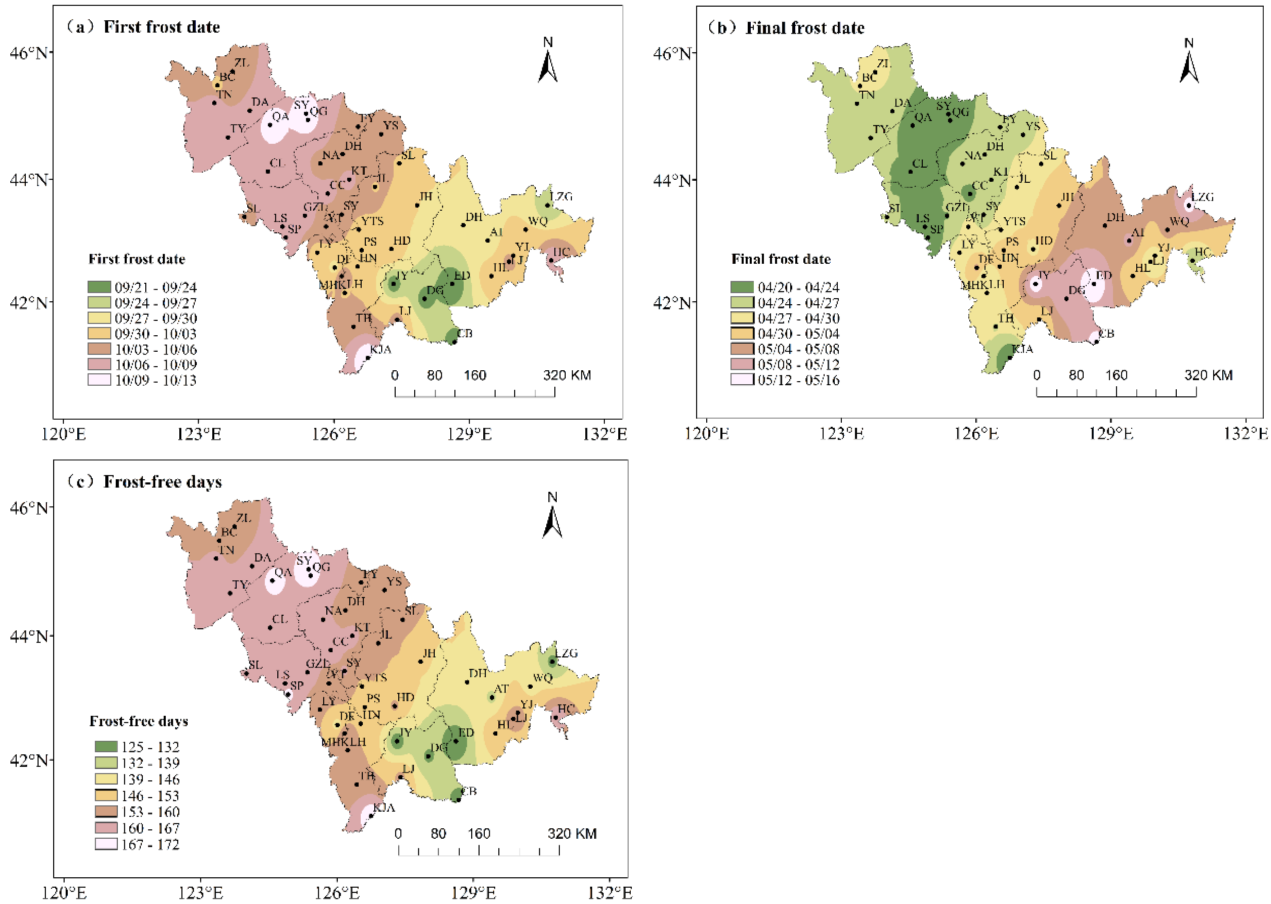


Fig.2 The space distribution of frost in Jilin Province from 1969 to 2020

3.2 Variation characteristics of frost dates

3.2.1 Climatic trend of frost dates

Figure 3 displays the interannual and interdecadal variations of the average first and last frost dates, as well as the duration of frost-free days in the Jilin region from 1969 to 2020. It is evident from Fig. 3 that there has been a significant delay in the first frost date over the past 52 years, with an average delay of 2.1 days per decade. The average first frost date is September 28th. In the 1970s, 1980s, and early 1990s, the first frost dates were earlier than the average by 2-5 days, while in the 2000s to 2020s, they were delayed by 3-5 days, demonstrating a phase shift in "earlier-later" trends [Fig. 3(a)]. Looking at the interdecadal changes, there is an overall upward trend with intermittent downward phases. The frequency histogram reveals a relatively even distribution, with the highest frequency of occurrence falling within the interval of [September 22nd to October 1st]. On the other hand, the last frost date exhibits a significant advancement trend, as shown in Fig. 3(b), with a rate of change of 2 days per decade (2 d·$(10a)^{-1}$), and the date lies within the range of [April 21st to May 11th]. In terms of interdecadal changes, the latest occurrence of the last frost in the 1970s was May 3rd, while the earliest occurrence in the 2010s was April 26th, showing a decreasing trend in a step-like pattern. The frequency histogram indicates that the interval [April 25th - April 28th] has the highest frequency, followed by the interval [April 29th - May 2nd]. The number of frost-free days is significantly increasing at a rate of 3.2 days per 10 years (3.2 d·$(10a)^{-1}$) [Fig. 3(c)]. In terms of interdecadal changes, the 2010s had the longest duration of 163 days, while the 1970s had the shortest duration of 151 days. The growth rate was faster in the 20th century, but slowed down in the 21st century, overall exhibiting a step-like upward trend. Looking at the frequency histogram, the interval [148, 154] had the highest frequency. In conclusion, the frost dates in Jilin region show a general trend of later first frosts, earlier last frosts, and an extended number of frost-free days. The interannual variations indicate that the magnitude of change follows the order of frost-free days > first frost date > last frost date.

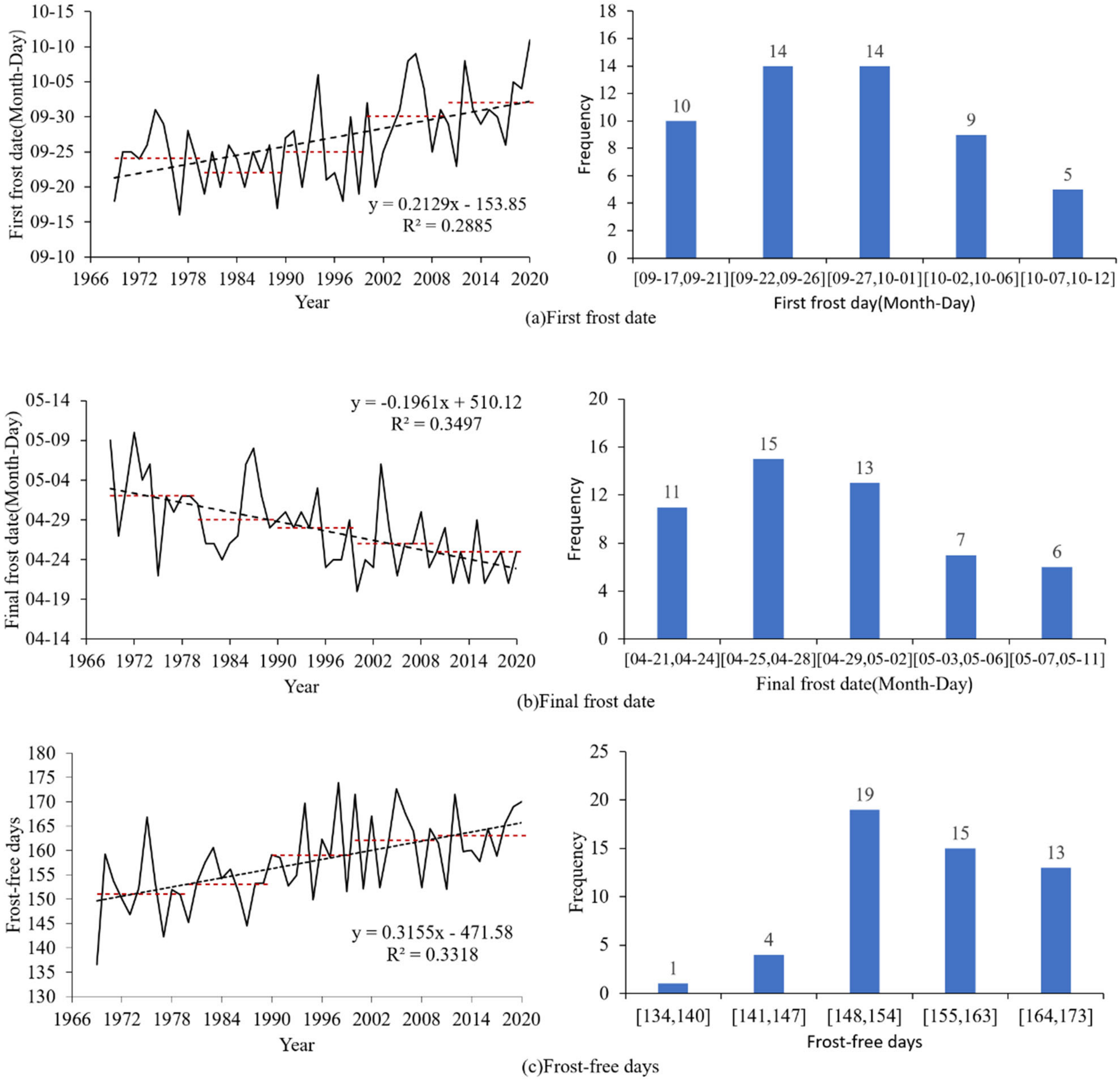


Fig.3 The inter-annual change (left)of frost date and frequency histogram (right) in Jilin Province

3.2.2 Analysis of sudden change of frost date

In order to further analyze the characteristics of frost dates in Jilin Province, M-K test and moving t-test were conducted on the interannual variations of frost dates. From Fig. 4(a), it can be observed that for the first frost date, the M-K test, at a significance level of 0.05 and within the ±1.96 confidence interval, shows three intersections between the UF and UB curves, which are in the years 2004, 2007, and 2009. These years are likely to have abrupt change points. After 2004, the UF curve shows an upward trend, indicating a delay in the first frost date. As shown in Fig. 4(b), between 2001 and 2005, the moving t-curve exceeds the confidence interval of ±2.145, suggesting the possible presence of an abrupt change point during this period. Combining the M-K test and the moving t-test, it can be concluded that the abrupt change point for the first frost date occurred in 2004. For the last frost date [Fig. 4(c), Fig. 4(d)], at a significance level of 0.05 and within the confidence interval of ±1.96, there is a clear intersection between the UF and UB curves in the year 1997. Moreover, the UF curve shows a downward trend and exceeds the confidence interval after 2005, indicating a significant advancement in the last frost date. The moving t-curve exceeds the confidence interval between 1994 and 2007, indicating the presence of an abrupt change point during this period. Combining the M-K test and the moving t-test, 1997 is identified as the abrupt change point for the last frost dates. For the frost-free period [Fig. 4(e)], at a significance level of 0.05 and within the confidence interval of ±1.96, the UF and UB curves still have a clear intersection point in 1991. Moreover, the UF curve shows an upward trend after 1991 and exceeds the confidence interval after 1997, indicating an extension of the frost-free period. In the years 1992-1993, the moving t curve exceeds the confidence interval, while during other periods it does not from Fig. 4(f). Therefore, the potential abrupt change point for the frost-free period may be in these two years. Combining the M-K test and the moving t-test, 1991 is identified as the abrupt change point for the frost-free period. In conclusion, the years of abrupt changes for the first frost dates, last frost dates, and frost-free period are 2004, 1997, and 1991, respectively. Climate warming has a significant impact on the increase in frost-free days, and the decadal change of temperatures in Jilin Province shows a rapid increase from the late 1980s to the early 2000s [26], with changes in frost dates and the frost-free period being mainly attributed to climate change.

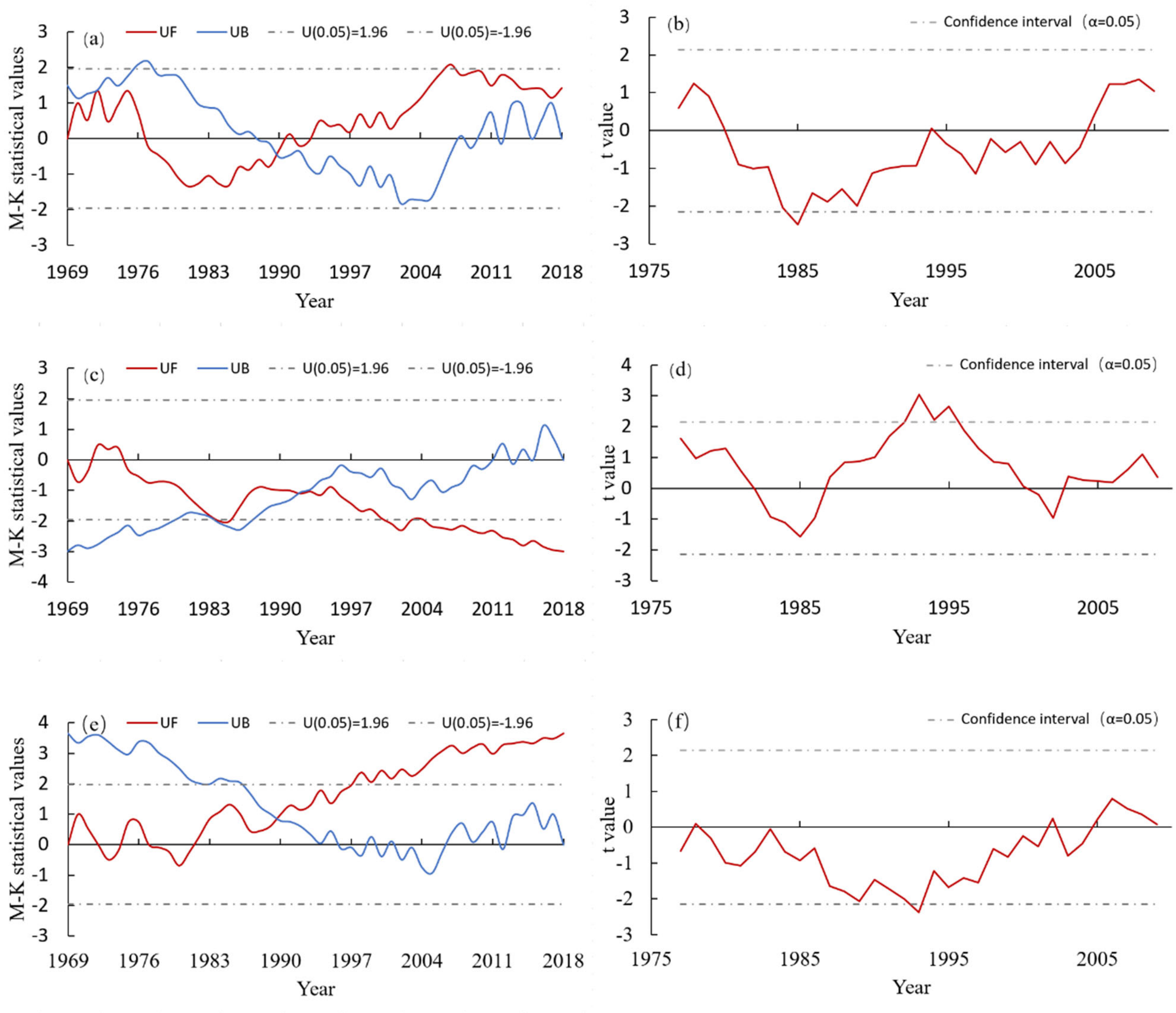


Fig.4 The M -K mutation test (left) and t test (right) of the frost date（numbers） in Jilin Province, where (a) and (b) are the dates of first frost, (c) and (d) are the dates of final frost, and (e) and (f) are the number of frost-free days

3.3 Spatial distribution of frost-free days

3.3.1 Zoning of frost-free days regions

According to the results of REOF analysis, the cumulative contribution of variance for each eigenvector reaches 64.77%. The first feature vector has the highest contribution rate of 40.55%, significantly surpassing the other two eigenvectors. The contribution rate of the second eigenvector is 15.74%, while the third eigenvector contributes 8.48% of the total variance.

Based on the rotated component matrix obtained from REOF analysis and the North criterion, the frost-free days regions in Jilin Province were divided into three Zones [27-28]. The regional classification results are shown in Fig. 5. Zone I (mainly in the northwestern part of Jilin, including southern Tonghua, Jilan, and Hunchun) includes the following meteorological stations: Zhenlai, Baicheng, Taonan, Da'an, Tongyu, Qian'an, Songyuan, Qianguo, Changling, Nongan, Dehui, Fuyu, Changchun, Lishu, Jilan, and Hunchun. Zone II (central and southern parts of Jilin) includes the following meteorological stations: Yushu, Shulan, Jiutai, Jiaohe, Shuangyang, Gongzhuling, Siping, Yitong, Yantongshan, Liaoyuan, Panshi, Huadian, Dongfeng, Huinan, Meihekou, Liuhe, Tonghua, and Linjiang. Zone III (mainly in the eastern part of Jilin, including Shuangliao and Jilin) includes the following meteorological stations: Dunhua, Luozigou, Wangqing, Antu, Longjing, Yanji, Helong, Erdao, Jingyu, Donggang, Changbai, Shuangliao, and Jilin.

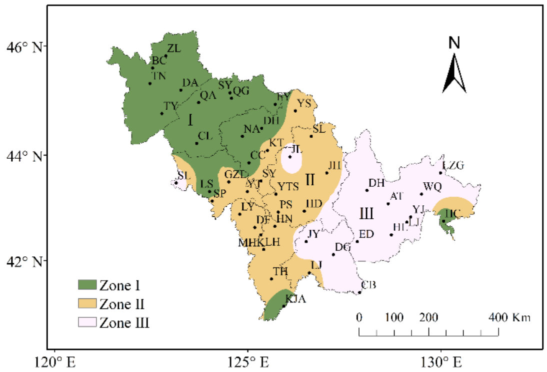


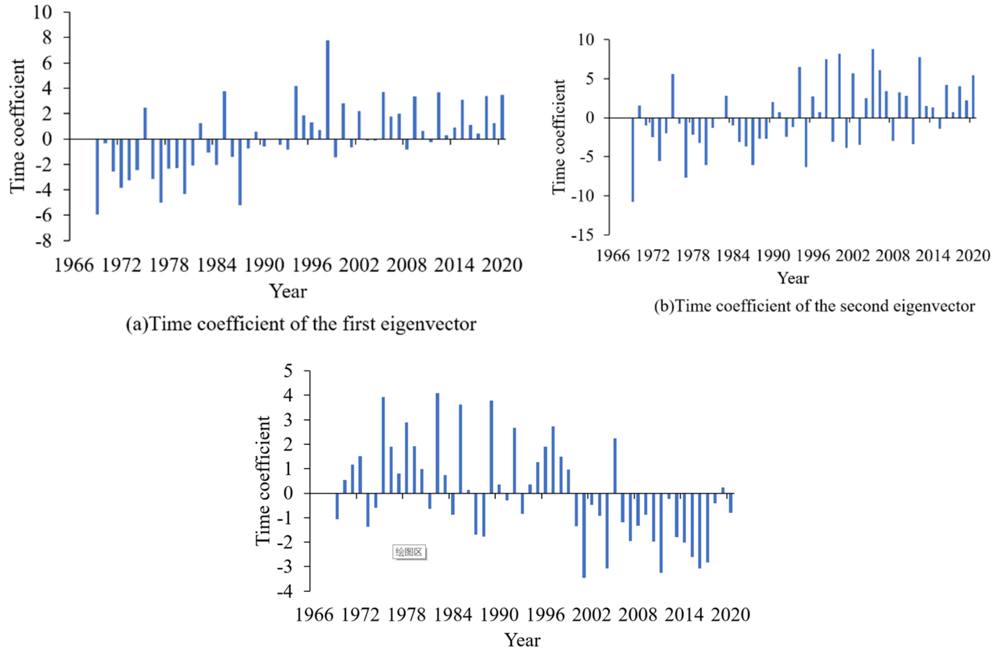
Fig.5 The zonal map of frost-free days in Jilin Province from 1969 to 2020

3.3.2 Temporal variation characteristics of frost-free days in each zone

In the northwestern region of Jilin Province (Zone I), it can be observed from the first modal time coefficient [Fig. 6(a)] that the year 1995 serves as a turning point. During the period from 1969 to 1994, the time coefficients were mostly negative, indicating a decrease in frost-free days during this period. However, after 1995, the time coefficients increased and were predominantly positive. This indicates a trend of increasing frost-free days in the northwestern region, particularly starting in the mid to late 1990s, with a noticeable shift towards a longer duration.

In the central and southern regions of Jilin Province (Zone II), it can be observed from the second modal time coefficient [Fig. 6(b)] that the year 1997 serves as a turning point. During the period from 1969 to 1996, the time coefficients were mostly negative, indicating a decrease in frost-free days during this period. However, after 1997, the time coefficients increased, with an amplified fluctuation amplitude, and were predominantly positive. This indicates a trend of increasing frost-free days in the central and southern regions, particularly starting in the late 1990s, with a noticeable shift towards a longer duration.

In the eastern region of Jilin Province (Zone III), it can be observed from the third modal time coefficient [Fig. 6(c)] that the year 2000 serves as a turning point. During the period from 1969 to 1999, the time coefficients were mostly positive. However, after 2000, the time coefficients decreased significantly and became predominantly negative. This indicates a trend of decreasing frost-free days in the eastern region since the beginning of the 21st century, with a noticeable shift towards a shorter duration.



(a)Time coefficient of the first eigenvector

(b)Time coefficient of the second eigenvector

(c)Time coefficient of the third eigenvector

Fig.6 Time coefficient of characteristic vector of frost-free days in Jilin Province

4. Conclusions

From 1969 to 2020, the overall spatial distribution pattern of the first frost date, last frost date, and number of frost-free days follows the trend of "earlier in the northwest, later in the southeast", "later in the southeast, earlier in the northwest", and "longer in the northwest, shorter in the southeast". In Jilin Province, the most common period for the occurrence of the first frost date is between September 22nd and October 1st, while the most common period for the occurrence of the last frost date is between April 25th and May 2nd. Overall, there is a trend of delayed first frost dates, advanced last frost dates, and extended number of frost-free days. The interannual variation magnitude follows the order of number of frost-free days > first frost date > last frost date.

The years of abrupt changes in the first frost date, last frost date, and number of frost-free days in Jilin Province were 2004, 1997, and 1991, respectively. The extension of the number of frost-free days is attributed to the decreased stability of the initial and last frost dates.

Based on the REOF analysis and the North criteria, the number of frost-free days in Jilin Province can be divided into three zones: the northwest region (Zone I), the central-southern region (Zone II), and the eastern region (Zone III). During the study period, Zones I and II showed a trend of shortening followed by extension of the number of frost-free days, while Zone III showed a trend of extension followed by shortening.

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