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Abstract: In this study, based on frost formation data provided by Harbin Meteorological Bureau, combined with geographical factors, temperature and population density, linear fitting, Mann-Kendall mutation test, pettitt method and sliding T test were used to analyze the spatio-temporal variation characteristics of frost date in Harbin Municipality and the effects of geographical factors, temperature and population density on frost regularity. The results showed that (1) The earliest year of FSD appeared was 1966 and 1967, on the 255th, i.e., August 18th, and the latest was 283 days, i.e., October 10th, 2006. The earliest year in which the FED appeared was April 24th of 2015, the 114th day of that year, and the latest was April 21st of 1974, the 141st day of that year. The year with the most frost was 2012, with 161 days, and the year with the shortest was 1966, with 123 days. (2) Throughout the study period, FSD increased by 7.8 days at a rate of -1.27d/10a, FED increased by 10.9 days at a rate of 1.77d/10a, and FFS increased by 18.9 days at a rate of 3.05d/10a. The tendency rate of FSD and FFS at each site in Harbin showed an increasing trend. For FED, the tendency rate of some sites showed an increasing trend. In general, FSD showed a delayed trend, FED showed an advanced trend, and FFS showed a prolonged trend. Using the method of unary linear regression, FSD of each site showed an increasing trend, FFS showed an increasing trend, and FED showed a decreasing trend in general. (3) Throughout the study period, FSD was mutated in 2000, and the arrival time of it in the study area averaged the 265th, i.e., September 22nd, and after that, the arrival time of it changed to the 272nd, i.e., September 29th of that year. FED was mutated in 2006, and the arrival time of it in the study area averaged 128th, i.e., April 8th. After the mutation, the arrival time of FED changed to 121st, i.e., April 1st of that year. FFS was mutated in 2004. Before the mutation, with an average arrival time of 137days in the study area .But after that, the time changed to 150 days.(4) FSD and FFS in Harbin Municipality were negatively correlated with latitude and positively correlated with temperature, while FED was positively correlated with latitude and negatively correlated with temperature. The FSD, FED and FFS in the central part of Harbin Municipality were the earliest, the latest and the longest, respectively, so the Pearson correlation coefficient method and the influence of longitude could not be reflected in the multiple regression. Several factors were judged by grey correlation analysis method. The longitude is significantly related to FSD, FED and FFS.

Keywords: frost; cold region; M-K test; meteorological factors; temporal and spatial variations

1. Introduction

Harbin is located in the high latitude cold zone [1]. In recent years, frost disaster has been one of the major crop disasters in the study area. Therefore, based on the meteorological data from 1961 to 2022, this study used linear fitting and Mann-Kendall mutation test to analyze the change characteristics of frost date and time in Harbin. Pearson method and multiple linear regression were used to analyze geographic factors, temperature and population density. With reference to previous

studies, taking the minimum surface temperature ≤0°C as the index of frost[2], the date of frost formation in northern China is basically after August 1. Therefore, in this study, the first date of frost formation after August 1 is called the Frost Star Date (FSD), and the last date of frost formation before August 1 is called the Frost End Date (FED). The period between FED and FSD is called the Frost-Free Season (FFS). This article converts the date of each year into the form of a numeric symbol, that is, the January 1 diary is 1, the March 1 diary is 60, and the March 1 diary is 61 in leap years.

In recent years, as the global temperature has risen, the temperature in the 2010s has increased by 1.09 ° C compared with the mid-19th century to the late 19th century. [3] The spatiotemporal variation of frost and the disasters caused by extreme weather have attracted wide attention from scholars around the world.Snow and ice are essential components of the global hydrological and energy cycles, and they are closely associated with the frost occurrence[4] Frost will have an important impact on the regulation of a Municipality's reservoir, and it is an important part of the hydrological facilities, infrastructure construction, winter tourism and so on.[5]FSD, FED and growing season length will have a certain impact on annual runoff, drought frequency, evaporation, etc.[6] Extreme disasters can make the same plants have different access to nutrients, leading to differences in plant growth,[7] and reproduction.[8] Frost damage can cause great damage to wheat,[9–11] persimmon,[12] broad beans[13] and other crops[14–17]. If the plant is born for a long time in the frost period, it will be greatly affected, not only the economic loss, but also the ecological environment will be greatly affected. In Europe, warming in early spring results in a "false spring", in which plants are more vulnerable to frost.[18] Some scholars say that early spring can lead to premature development of plant organs, causing vulnerable plant organs to be exposed to cold weather, leading to greater damage to plants.[19] In the United States, late frost can have different effects on different species of Ozark tree species, but estimating damage is difficult because there is no significant link between damage and later growth.[20]

At the same time, frost will also affect the impact resistance of reinforced concrete beams[21]. The result is carbonation of reinforced concrete, which reduces the durability of the original structure[22]. Frost damage will affect the viscosity of coarse aggregate reinforced concrete and ordinary reinforced concrete.[23,24]. At the same time, pervious concrete is more susceptible to damage in frost conditions.[25]

With the global warming trend, With the trend of global warming, all regions are facing the problem of increasing FFS. In 1973, the annual number of frost days in China was about 2d higher than the average from 1961 to 1990. From 1973 to 1985, the annual number of frost days was close to the average level, and the inter-annual change was very small; After 1985, the annual number of frost days decreased rapidly, and the reversal was obvious around 1992. The initial extension of FFS lagged behind the rapid increase in daily minimum temperatures by about 10 years, while the decrease in the number of annual frost days lagged by about 15 years.[26] The contribution of altitude to frost day variation is 96-100%. The vertical gradient of frost day is about 7 days /100 m. During the period 1936-2013, the long-term trend of frost day was not significant, and the frost day change rate was basically negative, not less than -1.5 days per decade. During the most intense global warming, the frost day change rate is less than -3 days per decade and, in some cases, equal to -15 days per decade.[27] Due to the unique topography of the Libyan Peninsula (IP), frost days vary widely, with the general trend being 0.4-1.6 days later for FSD per day and 0.42-1.29 days earlier for FED per year.[28] In the United States from 1948 to 1999, FSD showed a trend of delay, FED showed a trend of advance, and FFS showed a trend of extension.[29] Although the temperature in South Korea has increased year by year, frost day and FSD have not increased or delayed, and even the last frost date has been delayed by 0.5 days per year.[30] In Japan, the first frost date is delayed by 0.224 days per year, and the last frost date is advanced by 0.228 days per year. Sites with strong winds contributed to a decrease in the temperature criterion.[31]

So far, few efforts have been made to describe the nature of these changes in space and time, especially in relation to other variables. In this study, not only geographical factors, but also temperature and population density are analyzed and discussed. Understanding the changes of FSD,FED and FFS in Harbin is of great significance for global warming research and agricultural

production. The purpose of this study is to: (1) analyze the spatio-temporal variation characteristics of FSD,FED and FFS indices in Harbin during 1961-2022; (2) explore the relationship between FSD,FED and FFS and temperature and population density in Harbin.

2. Study Area, Data Sources, and Methods

2.1. Study area

The study area is located in Harbin, Heilongjiang Province, China (125°42 '-130°10' E and 44°04 '-46°40 N) ,which is a representative Municipality of the high-latitude cold zone. It covers an area of about 53,000 square kilometers, with an average altitude of 118.3m. The climate is characterized by a mid-temperate continental monsoon, with an average annual temperature of about 4.1°C, an average annual maximum temperature of 9.6°C, an average annual minimum temperature of -2.2°C, an average annual wind speed of about 5.5 m/s, and an average annual humidity of about 70%.[1,32] Figure 1 shows the geographical location of the study area, geomorphological features and the location of meteorological stations. Table 1 shows the codes and names of each meteorological station.
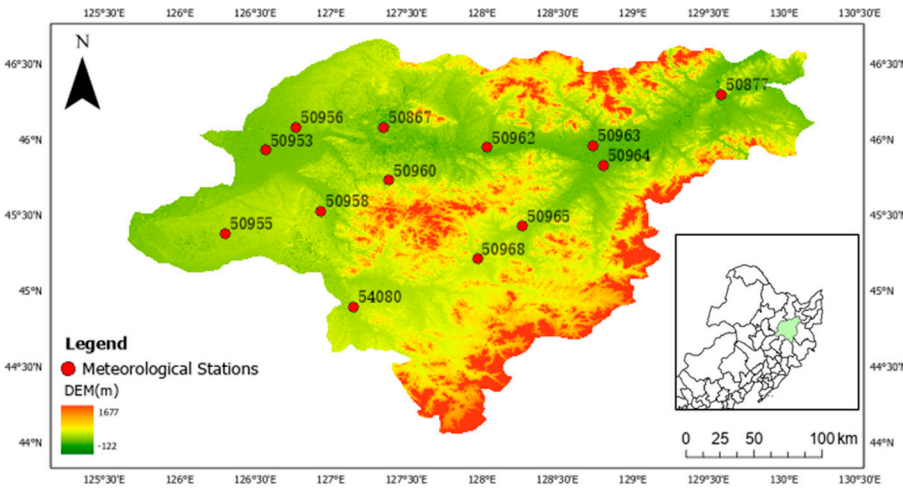

Figure 1. Study area and distribution of meteorological stations.

2.2. Data Sources

The meteorological data used in this study are the 0-cm surface air temperatures of 13 meteorological stations in Harbin, provided by the Harbin Meteorological Bureau. This study utilizes a 30m spatial resolution digital ground model provided by the Japan Aerospace Exploration Agency (JAXA) to obtain digital elevation data (DEM) for Harbin. Population density data were obtained from seven censuses in China, of which the first through sixth census data were from the website of Scientific Data of China[33](http://www.csdata.org/p/574/), and the data of the seventh census were from the official website of the Harbin Municipal People's Government(https://www.harbin.gov.cn/haerbin/c104569/202105/c01_70396.shtml).

2.3. Methods

In this study, the trend of key variables was analyzed by linear trend fitting, the significance of it was tested by Mann-Kendall mutation test, and the authenticity of mutation points was tested by pettitt method and sliding T test. Ordinary Kriging interpolation method is used to interpolate the key variables of frost from the point scale to the regional scale. Considering that the factors affecting the key variables of frost include not only latitude and longitude, but also altitude, this study takes altitude as a covariate to improve the longitude of interpolation. Pearson correlation coefficient method and multiple linear regression were utilized to calculate the correlation and regression of elevation, longitude, latitude, air temperature and population density with the key variables of frost.

Table 1. Names of different meteorological stations.

Station	Name	Station	Name
50867	Bayan	50962	Mulan
50877	Yilan	50963	Tonghe
50953	Harbin	50964	Fangzheng
50955	Shuangcheng	50965	Yanshou
50956	Hulan	50968	Shangzhi
50958	Acheng	54080	Wuchang
50960	Binxian	——	——

3. Results

3.1. Temporal and spatial variation and mutation test of FSD

Figure 2 shows the spatial distribution of FSD in Harbin during 1961-2022. From Figure 3, it can be seen that the FSD arrives earlier in the south-central part of Harbin and later in the western part. The overall trend is a gradual advancement from the east and west ends to the center. The FSD in Harbin is between the 264th and 272nd, i.e., September 21st to September 29th of the year. Figure 4 shows the overall variation of FSD in Harbin, which shows a delayed trend from year to year. The FSD increased by 7.8 days at a rate of -1.27 d/10a throughout the study period .The earliest FSD was in 1966, on the 255th, i.e., September 18th of that year, and the latest was in 2006, on the 283rd, i.e., October 10th of that year. We used the Mann-Kendall mutation test to check the significance of the change trend of FSD, and used the pettitt method and the sliding T test to check the authenticity of the mutation points. The results showed that FFD was mutated in 2000 by Mann-Kendall mutation test. And the mutation points passed the significance test of $\alpha = 0.05$ by pettitt method and sliding T test, indicating that there were significant differences between mutation points. Before the mutation, the average arrival time of FSD in the study area was 265d, i.e., September 22nd of that year and after that, the arrival time averaged to be the 272nd, i.e., September 29th of that year.
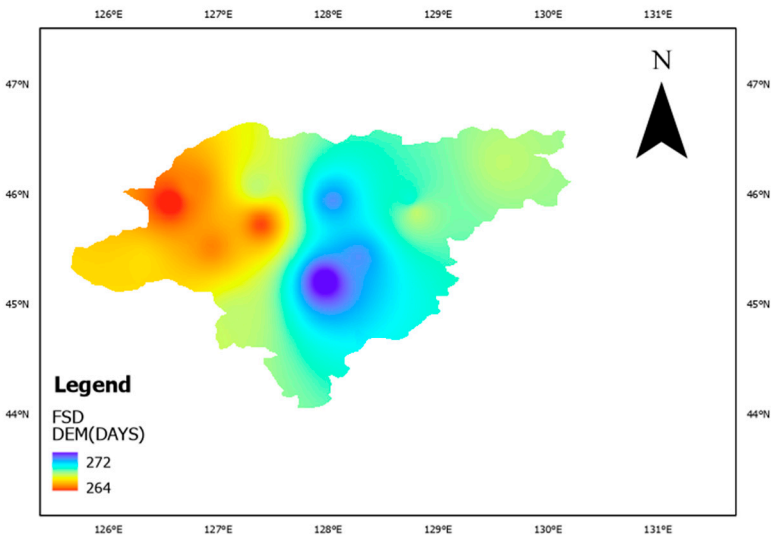

Figure 2. Spatial distribution of FSD in Harbin Municipality from 1961 to 2022.
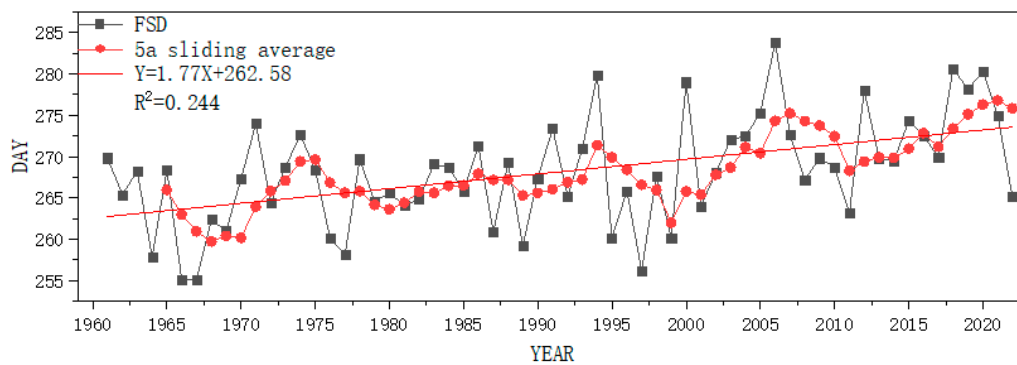
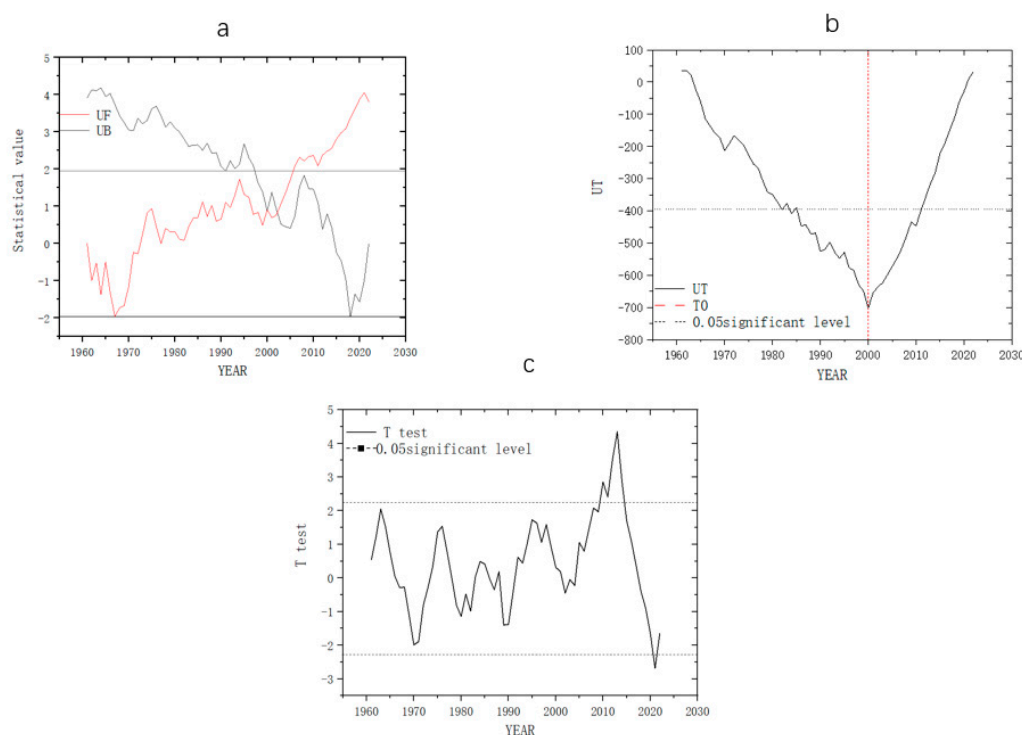**Figure 3.** Interannual variation in FSD in Harbin Municipality.

Figure 4. M-K(a), pettitt(b), sliding t-test(c) of FSD in Harbin Municipality.

3.2. Temporal and spatial change and mutation test of FED

Figure 5 shows the spatial distribution of FED in Harbin during 1961-2022. From Figure 6, it can be seen that the FED arrived later in the south-central part of Harbin, while earlier in the west. The overall trend is a gradual postponement from the east and west ends by toward the center. The FED days in Harbin are between the 121st and 135th days, i.e., from April 1st to April 15th. Figure 7 shows the overall change of the FED in Harbin, with a trend of delay from year to year. The FED increased by 10.9 days at a rate of 1.77d/10a throughout the study period.The earliest year of FED was 2014, on the 114th day of the year i.e., April 24th of that year, and the latest year was 1974, on the 141st day of the year i.e., May 11th of that year. The FED increased by 10.9 days at a rate of 1.77d/10a throughout the study period.The earliest year of FED was 2014, on the 114th day, i.e., April 24th, and the latest was 1974, on the 141st, i.e., May 11st of that year. We used the Mann-Kendall mutation test to check the significance of the change trend of FED, and tested the veracity of the mutation points by the pettitt method and the sliding T test. By Mann-Kendall mutation test it was concluded that the mutation of FED in 2000 was tested by Mann-Kendall mutation test,and the mutation point passed

the significance test of α = 0.05 by pettitt method and sliding T test, indicating that there were significant differences between mutation points. Before the mutation, the arrival time of FED in the study area averaged 128th , i.e., April 8th, and after that, the arrival time of FED averaged 121st d, i.e., April 1st of the year.
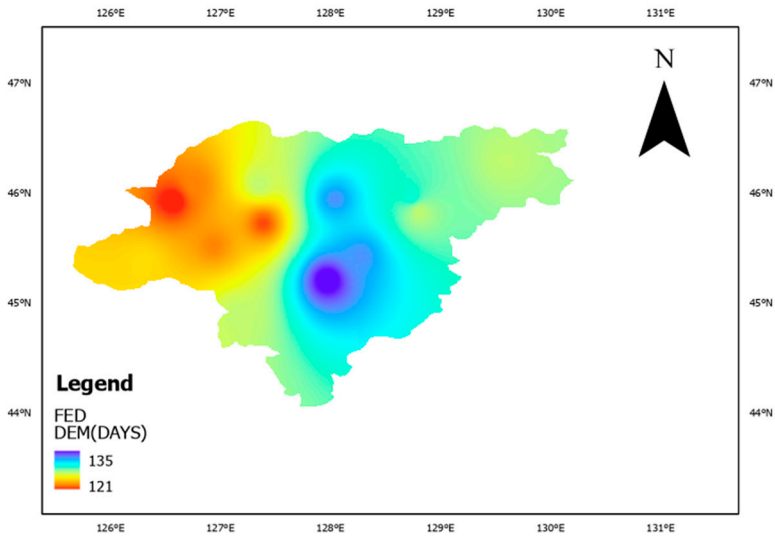

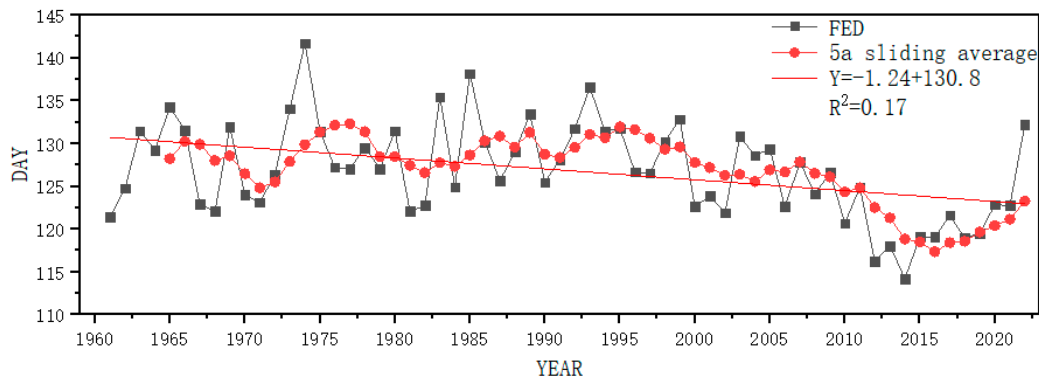**Figure 5.** Spatial distribution of FED in Harbin Municipality from 1961 to 2022.

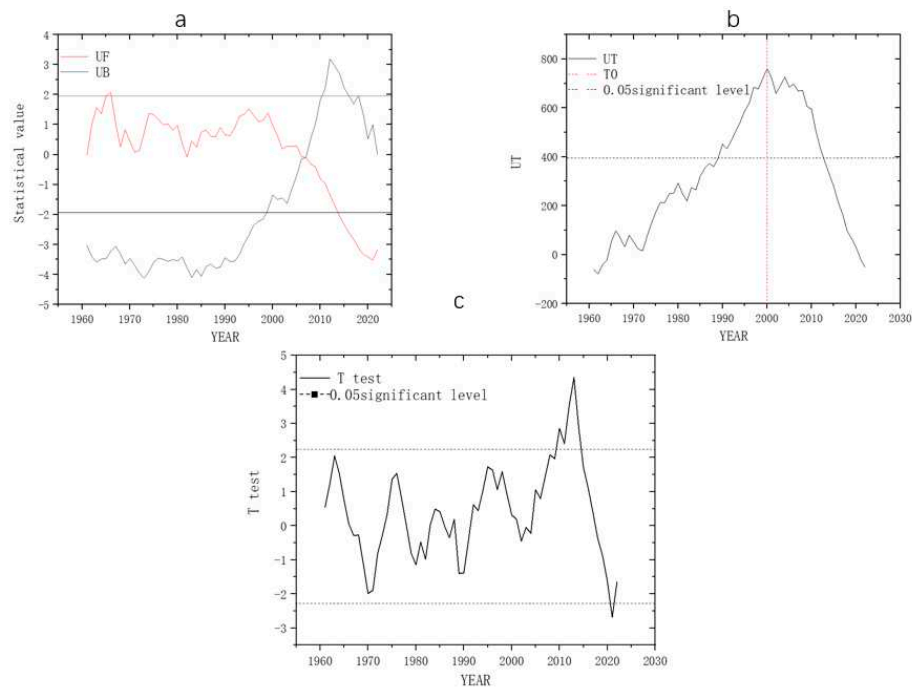**Figure 6.** Interannual variation in FED in Harbin Municipality.

Figure 7. M-K(a), pettitt(b),sliding t-test(c) of FSD in Harbin Municipality.

3.3. Test of spatio-temporal variation and abrupt change of FFS

Figure 8 shows the spatial distribution of FFS in Harbin from 1961 to 2022. It can be seen from Figure 9 that the FFS is later in the south-central part of Harbin, while FFS in the western part is longer. The overall trend is decreasing from the east and west ends to the center, and the number of days of occurrence is in the range of 129-149 days. Figure 10 shows the overall change of FFS in Harbin, presents a trend of lengthening year by year. FFS increased by 18.9 days at a rate of 3.05d/10a throughout the study period, with the highest FFS in 2012 (161 days) and the shortest FFS in 1966 (123 days). We used the Mann-Kendall mutation test to check the significance of the trend of the FFS and the pettitt method and sliding T test to check the authenticity of the mutation points. The results showed that the mutation of FFS occurred in 2004 by Mann-Kendall mutation test, and the significance test of $\alpha = 0.05$ by pettitt method and sliding T test, indicating that there were significant differences among mutation points. Before mutation, the average FFS in the study area was 137d. After the mutation, FFS averaged 150 days in the study area.
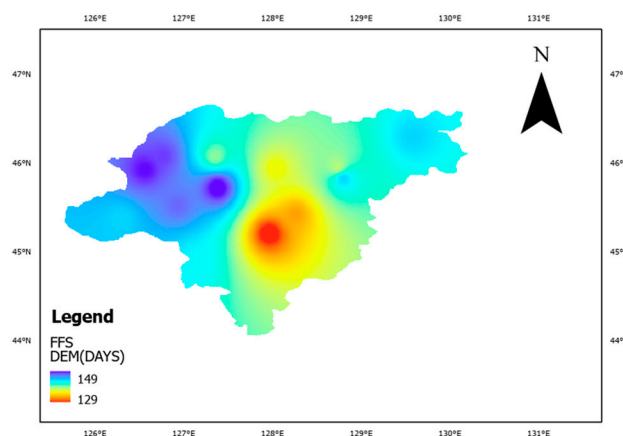

Figure 8. Spatial distribution of FFS in Harbin Municipality from 1961 to 2022.
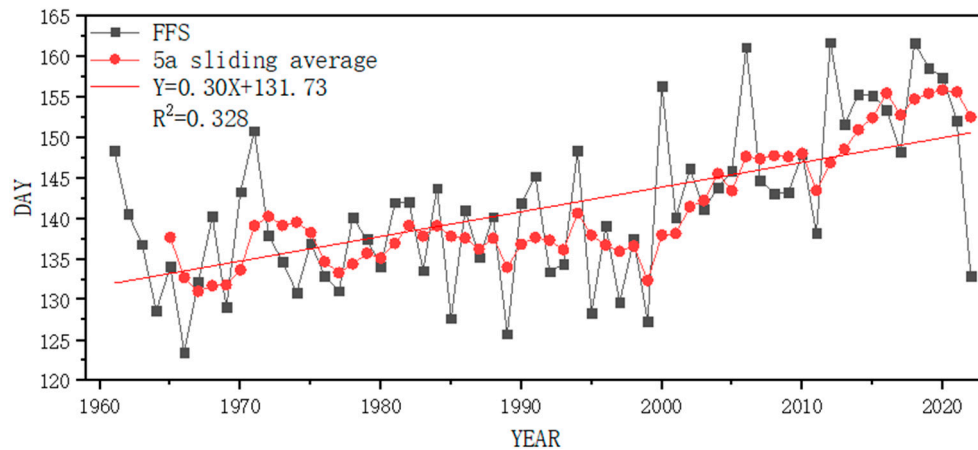
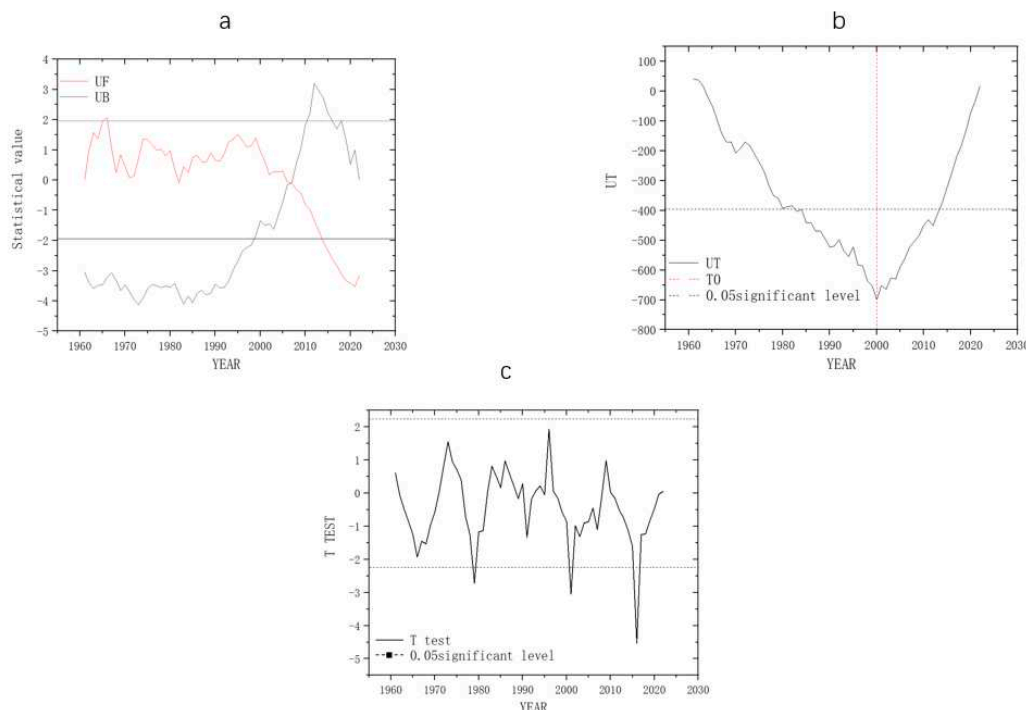**Figure 9.** Interannual variation in FED in Harbin Municipality.

Figure 10. M-K(a),pettitt(b),sliding t-test(c) of FFS in Harbin Municipality.

3.4. Factors influencing of frost

The correlations and regression coefficients of FSD, FED and FFS with geographic factors, mean temperature and population density in Harbin are shown in Table 2. FSD, FED and FFS with temperature r are 0.363, -0.614 and 0.557.FED and FFS are significantly correlated with temperature, whereas the correlations with both geographic factors and population density are not significant. The regression coefficients show that for every 1° increase in latitude FSD will be advanced by 1.44 days, FED will be delayed by 5.15 days and FFS will be prolonged by 6.6 days. For every 1°C increase in mean temperature FSD will advance by 1.38 days, FED will be delayed by 3.026 days and FFS will be prolonged by 4.409 days. In Harbin，FSD and FFS are negatively correlated with latitude and positively correlated with temperature, while FED is positively correlated with latitude and negatively correlated with temperature. The FSD, FED and FFS in the central part of Harbin Municipality are the earliest, latest and longest, respectively, so the influence of longitude cannot be reflected in Pearson correlation coefficient method and multiple regression analysis method.

Table 2. Relationships of the FSD, FED and FFS with the geographical parameters, average temperature and population in Harbin Municipality.

Factor	IF	FSD	FED	FFS
CC	ASL	-0.05	-0.048	0.016
	LAT	0.523	-0.121	0.165
	LON	0.147	-0.134	0.145
	TEMP	0.363	-0.614*	0.557*
	POP	0.187	-0.514	0.426
RG	ASL	0.007	-0.028	0.036
	LAT	1.314	-0.4164	5.478
	LON	-0.013	1.505	-1.519
	TEMP	1.383	-3.026	4.409
	POP	~0	-0.002	0.002

4. Discussion

In this study, we collected data on the number of frost days in Harbin for a total of 62 years from 1961 to 2022. Most of the annual FFS appeared in mid-late May to mid-early September, about 140 days; FSD appeared in mid- to late August; and FED appeared in mid- to early May. In the late 1950s and 1960s, FSD would advance to late August to early September and FED was delayed to early June each year. FSD appeared earliest in 1966 and 1967, both on the 255th, i.e., August 18th, and latest in 2006 on the 283rd, i.e., October 10th. FED appeared earliest in 2015 on the 114th, i.e., April 24th, and latest in 1974 on the 141st day, i.e., April 21st of that year. The most frosty year was 2012 with 161 days and the shortest was 1966 with 123 days.

4.1. Trends in FSD,FED and FFS

As shown in Table 3, the propensity rates for FSD and FFS showed an increasing trend for each site in Harbin. For FED, there was an increasing trend in the propensity rate for some sites. In general, FSD showed a delayed tendency, FED showed an advanced tendency, and FFS showed an extended tendency. Analysis using the method of unary linear regression showed an increasing tendency for both FSD and FFS at all sites, and an overall decreasing tendency for FED.

Using the mean values of the frost elements at each station, it can be seen that FSD appeared earliest at weather station 50968 on the 264th, i.e., September 21st, and latest at 50956 on the 270th, i.e., September 27th of the mean year. FED appeared earliest at 50953 on the 121st, i.e., May 1st of the mean year, and latest at 50968, on the 135th, i.e., March 15th of the mean year. The highest number of FFS occurrences was at weather station 50960, with a number of 149 days, and the lowest was at 50948, with only 129 days.

With global warming, FSD is delayed, FED is advanced and FFS is extended in Harbin, which will extend the growing season of the crops, provide sufficient heat resources for regional agricultural production, and facilitate the expansion of suitable planting areas for crop cultivation. Heilongjiang Province is a major grain producing area in China, and the sensitivity of crop growth to frost will vary with different crops and climatic conditions. Therefore, different systems and methods are needed to reduce the damage of frost to crops.

Table 3. Variations of the FSD, FED and FFS in different meteorological stations of Harbin Municipality from 1961 to 2022.

meteorological stations	FSD		FED		FFS	
	Ave.(d)	Tre.(d/10a)	Ave.(d)	Tre.(d/10a)	Ave.(d)	Tre.(d/10a)
50867	267	2.14	127	-1.87	139	4.01
50877	269	2.22	127	-1.64	143	3.86
50953	269	2.01	121	-2.23	148	4.24
50955	268	1.64	125	0.8	143	0.84
50956	270	1.52	123	0.27	147	1.25
50958	268	1.06	122	-0.21	146	1.27
50960	272	0.61	122	0.18	149	0.43
50962	267	2.09	132	-2.22	136	4.31
50963	267	1.92	129	-2.72	138	4.63
50964	270	1.59	127	-1.48	143	3.07
50965	265	1.78	132	-1.93	133	3.71
50968	264	2.91	135	-2.74	129	5.65
54080	269	1.59	127	-0.73	142	2.32
Ave.	268	1.77	127	-1.27	141	3.05

4.2. *Testing FSD,FED and FFS based on grey relational analysis*

Therefore, this study adopts grey correlation analysis method to judge several factors. The resulting grey correlation coefficient is shown in Table 4: The longitude has a high gray correlation with FSD,FED and FFS. Because the longitude has no linear relationship with FSD,FED and FFS, the longitude is not significant when using Pearson method and multiple regression method.

Table 4. Grey correlation coefficient of the FSD ,FED and FFS with the geographical parameters, average temperature and population in Harbin Municipality.

Factor	IF	FSD	FED	FFS
GCC	ASL	0.942967	0.939464	0.951001
	LAT	0.987238	0.975974	0.992901
	LON	0.988881	0.97644	0.993903
	TEMP	0.958773	0.971249	0.960265
	POP	0.848286	0.847311	0.857801

5. Conclusions

By analyzing the spatial and temporal variations of FSD, FED and FFS in Harbin and the effects of geographic factors, temperature and population density on them, the results show that:

(1) The earliest year in which FSD appeared was 1966 and 1967, both on the 255th day, i.e., August 18th, and the latest was 2006, on the 283rd day, i.e., October 10th.The earliest year of FED was 2015, on the 114th day, i.e., April 24th of that year, and the latest was 1974, on the 141st day, i.e., April 21st of that year. The longest year of frost was 2012 with 161 days and the shortest was 1966 with 123 days.

(2) Throughout the study period, FSD increased by 7.8 days at a rate of -1.27d/10a, FED increased by 10.9 days at a rate of 1.77d/10a, and FFS increased by 18.9 days at a rate of 3.05d/10a. The propensity rates of FSD and FFS at each site in Harbin showed an increasing trend. For FED, some sites showed an increasing trend. In general, FSD showed a delayed trend, FED showed an advanced trend, and FFS showed a prolonged trend. Using the method of unary linear regression, the sites showed an increasing trend for both FSD and FFS, and an overall decreasing trend for FED.

(3) During the whole study period, FSD was mutated in 2000, and the arrival time of FSD in the study area averaged the 265th, i.e., September 22nd. And after the mutation, the arrival time of it

changed to the 272nd, i.e., September 29th. FED was mutated in 2006, and the arrival time of FED in the study area averaged the 128th, i.e., April 8th of that year. After the mutation, it changed to the 121st, i.e., April 1st of that year. FFS was mutated in 2004, and FFS in the study area averaged 137 d prior to the mutation, after that, changed to 150d.

(4) In Harbin Municipality, FSD and FFS were negatively correlated with latitude and positively correlated with temperature, while FED was positively correlated with latitude and negatively correlated with temperature. The FSD, FED, and FFS in central Harbin are the earliest, latest, and longest, respectively, so the effect of longitude could not be captured when applying the Pearson correlation coefficient method and multiple regression methods. Several factors were judged by grey correlation analysis method. The longitude is significantly related to FSD, FED and FFS.

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