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The climate characteristics of the first date of ≤0 °C temperature in East China

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Abstract

In this paper the climate characteristics of the first date of ≤0 °C temperature are analyzed; furthermore, the farming responses to climate warming are discussed using a climate diagnosis analysis and the least squares methods, which are based on the daily minimum temperature data in East China from 1961 to 2009. It was found that over the past 50 years there has been a trend of the first date of ≤0 °C temperature being delayed at a rate of 1.6 days per 10 years; however, between 1961 and 1990 the first date of ≤0 °C temperature arrived early at a rate of 1.8 days per 10 years, and then was delayed at a rate of 3.3 days per 10 years. Furthermore, the average first date of ≤0 °C temperature is 30 October in northern regions, and the frequency of the first date of ≤0 °C temperature is greater in October and November than in other months; however, the boundary of the first date of ≤0 °C temperature shifts from south to north during September to December, and this has been especially evident since the 1990s. It was also found that in some southern stations, ≤0 °C temperature never occurs. The first date of ≤0 °C temperature occurs earlier in the north than in the south, and the interannual variation of the first date of ≤0 °C temperature is large in low latitudes and small in high latitudes. Additionally, the sustained period of ≤0 °C temperature, from beginning to end, decreased at a rate of 5 days per 10 years, which leads to a reduction in the length of the frost periods and causes a structural adjustment to the type of crops that can be planted. Therefore, the study reveals the significant effects that the first date of ≤0 °C temperature can have on the length of frost periods and farming and provides useful findings with regard to the prevention of frost damage and agricultural management.

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Introduction

Global climate is experiencing significant variations, with warming being a main characteristic. Various kinds of extreme weather events are occurring more frequently, which have, and will continue to have, a profound influence on crop farming in particular (Cheng, 2011; Li et al., 2011). The fifth evaluation report of the Intergovernmental Panel on Climate Change (IPCC) states that the linear trend rate of the global surface temperature was –0.6 to 2.5 °C $10a^{-1}$ between 1901 and 2012 (IPCC, 2013), and many scholars have been concerned about the high-latitude warming being more acute in the northern hemisphere (Beniston et al., 1997; Bonsal et al., 2001). The spatial distribution of the temperature has a direct influence on the ecological environment, vegetation distribution, agricultural crop species, agricultural plantation methods, the maturity of crops and the crop yield (Hao et al., 2010; Walther et al., 2002). Variations in the date of the arrival of ≤0 °C temperatures are an important factor that influence agricultural production and can affect the frequency of agro-meteorological disasters. The day in which the first frost occurs is subject to global warming and has a significant effect on agricultural planning and land resources, as well as the sustainable development of agriculture (Wang and Wang, 2011; Wendell, 2003). Studies have shown that globally, the number of frost days have diminished due to global warming. Notwithstanding, the first date of ≤0 °C temperature signals the beginning of the cryogenic season, and when the temperature continues to cool, it can lead to the occurrence of frost damage, which has an adverse effect on crops (Wang et al., 2009; Du et al., 2011; Xu et al., 2009). The number of frost days in continental Europe in the past few decades has been decreasing, and the extreme differences between the dates of the first frost and last frost and the length of the frost-free period were smaller in the north than in the south (Scheifinger et al., 2003). The number of frost days with daily temperatures ≤0 °C, has also been decreasing in the continental United States (Easterling, 2002). Numerical experiments and analyses of observations have shown that global warming has led to a general reduction in the number of frost days (Frich et al., 2002; Meehl et al., 2004). This is the case in most parts of China where the length of the frost period has gradually shortened (Zhai and Pan, 2003; Qian and Lin, 2004); moreover, since the 1990s, the date of the first frost has been delayed. The above studies and discussions were all focused on the length of the frost period of a single region. The first date of ≤0 °C temperature has a great influence on the first frost date and the duration of the frost-free period; however, few studies have been conducted on variations in climate characteristics related to the first date of ≤0 °C temperature.

In this paper, the surface observed data of the daily minimum temperature of the past 50 years are compiled, and variations in climate characteristics related to the first date of ≤0 °C temperature in East China are analyzed. The information can both help to guide the structural adjustment of the type of crops that can be planted and provide a basis for the prediction and prevention of frost damage and cold injuries to plants in general.

The Location and Measurement Program

There are significant geographical differences between Eastern and Western China. There is a drought in the western part of the coun-

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try, yet cold injuries are more serious here. A change in temperature has a significant impact on the crop yield of East China, which is located between 18°15′–53°48′N and 109°30′–133°97′E. It includes the provinces of Heilongjiang, Jilin, Liaoning, East Inner Mongolia, Hebei, Tianjin, Beijing, Shandong, Anhui, Jiangsu, Zhejiang, Jiangxi, Fujian, Guangdong, and Hainan. Frost disasters occur almost every year, and the date of this frost is related to the first date of ≤0 °C temperature. The daily minimum surface temperature data used in this study were obtained from the China Meteorological Information Center (CMIC). The daily minimum temperature is air temperature measured at 1.5 m above the ground surface and is measured by a minimum thermometer. A minimum thermometer is used solely to determine the time interval (usually one day) of the lowest air temperature. It is placed horizontally in the wooden shutter of a Venetian Box (the same as a Stevenson screen), with a bulb on top, both on the left and right. The Venetian Box is placed 1.5 m above the ground surface. The minimum air temperature is observed once a day at 8:00 p.m., and if the observed reading finds that the minimum thermometer alcohol column is interrupted, the lowest air temperature is recorded as missing. After each observation, the thermometer needs to be adjusted, and a correction of the reading is processed between the 1st and 5th of each month at 8:00 p.m. In the statistical data, one year was defined as being between 1 July of one year and 30 June of the next year. Furthermore, the first date of ≤0 °C temperature was defined as the earliest occurrence of that date in a year, and the end date as the last occurrence of that date in a year; subsequently an annual and monthly data sequence was constructed. Data quality assurance checks, including the climatic boundary value, extremes, elements of internal consistency and gross errors were performed by CMIC. Quality control was first conducted by the station, followed by the province, then by the state; while the linear regression model was applied to the missing meteorological record interpolation of the daily minimum temperature. In order to make the results more reliable in this paper, a network of stations of sufficient density were required for the analysis of climate change. Therefore the data from 1961 to 2009 for 360 stations across Eastern China were used (Fig. 1).

The changes of the first date of ≤0 °C temperature were analyzed using the climate diagnosis analysis method, while the trend values of the earliest date of the occurrence of ≤0 °C temperature were calculated by the least squares method. A positive value represents the first date of ≤0 °C temperature arriving early, a negative value indicates a delay in the first date of ≤0 °C temperature, and the absolute value gives the degrees of change. The interannual variability of the first date of ≤0 °C temperature was measured and the sliding t-test was employed to test the trend of the first date of ≤0 °C temperature. The long-term average of the first date of ≤0 °C temperature between 1961 and 2009 was also calculated. Based on the World Meteorological Organization (WMO) standard, which usually uses a 30 year period for the baseline average, the annual average of the first date of ≤0 °C temperature from 1971 to 2000 was taken as a standard to calculate anomalies. In addition, the empirical orthogonal function (EOF) decomposition method was

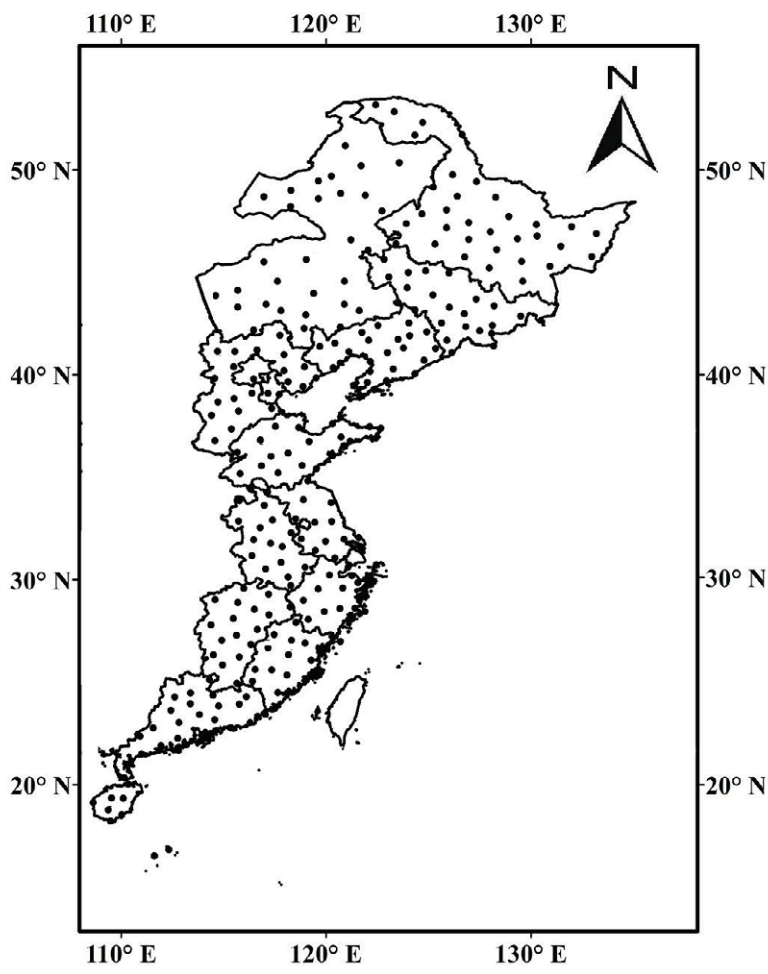

FIGURE 1. The station distribution in East China.

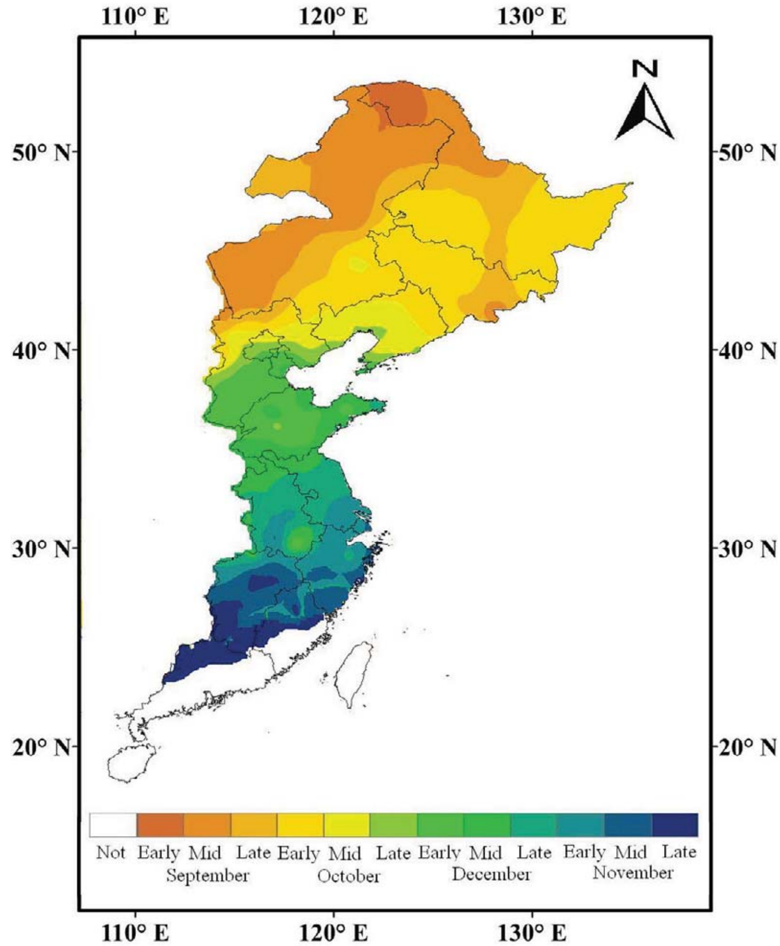

FIGURE 2. The annual average distribution of the first date of ≤0 °C temperature in East China.

used to analyze the spatial variation of the first date of ≤0 °C temperature, and to reveal regional climate differences.

Results and Discussion

THE SPATIAL DISTRIBUTION OF THE FIRST DATE OF ≤0 °C TEMPERATURE

Figure 2 displays the spatial distributions of the first date of ≤0 °C temperature. It can clearly be seen that in the past 50 years, from 1961–2009, the average first date of ≤0 °C temperature showed obvious regional differences in East China. The average first date of ≤0 °C temperature appears early in the northern regions in September followed by the intermediate regions in October and December, and then by the southern regions in November. Simultaneously, the earliest date occurred in the Heilongjiang province in August and the latest date occurred in the Guangdong province on 1 February the following year. In the northern, intermediate, and southern areas, the average first date of ≤0 °C temperature was 11 October, 17 November, and 18 December, respectively.

Figure 3 shows the EOF decomposition of the first date of ≤0 °C temperature. The cumulative variance of the two eigenvectors for the EOF was 66.7%, and passed the 95% t-test of significance. The first eigenvector ranged from –0.03 to –0.24 (see Fig. 3, part a), and the variance was 37.5%. The negative value shows that the variation trend of the first date of ≤0 °C temperature is consistent. The second eigenvector was positive in the south and negative in the north (see Fig. 3, part b). Its variance was 29.2%, which revealed the differences in the date between the north and south and also reflects that the first date of ≤0 °C temperature was earlier in the north and later in the south. It can be seen from Figure 4 that the time coefficient of the first eigenvector of the first date of ≤0 °C temperature significantly increased, and confidence levels reached 95%. The second eigenvector coefficient variation was not clear and indicated that the eigenvector of representative spatial consistency shows an increasing trend and the change is subject to the same climate factors.

From Figure 5, it can be clearly seen that the boundaries of the first date of ≤0 °C temperature moved from the south to the north between September and December. In the 1960s, the first date of ≤0 °C temperature appeared in Heilongjiang, Liaoning, Jilin, and East Inner Mongolia in September, whereas it was October in Tianjin and Hebei. Furthermore, in November it appeared in the Yangtze River basin, and in December it appeared in Fujian and Guangzhou (see Fig. 5, part a). In the 1970s, the first date of ≤0 °C temperature was delayed in the north, whereas it was early in the south (see Fig. 5, part b). In the 1980s, the boundaries of the first date of ≤0 °C temperature in September, October, November, and December shifted from the south to the north, and in particular in the 1990s and 2000s it shifted swiftly (Figs. 5, parts c–e). The distribution of the first date of ≤0 °C temperature is associated with the climatic environment in East China. In the area with a latitude of 39°N south, due to the monsoon circulation and a greater amount of water vapor, the annual average temperature rose significantly from the 1980s onward in China; moreover, in particular the daily minimum temperature increased greatly (Cheng, 2011;

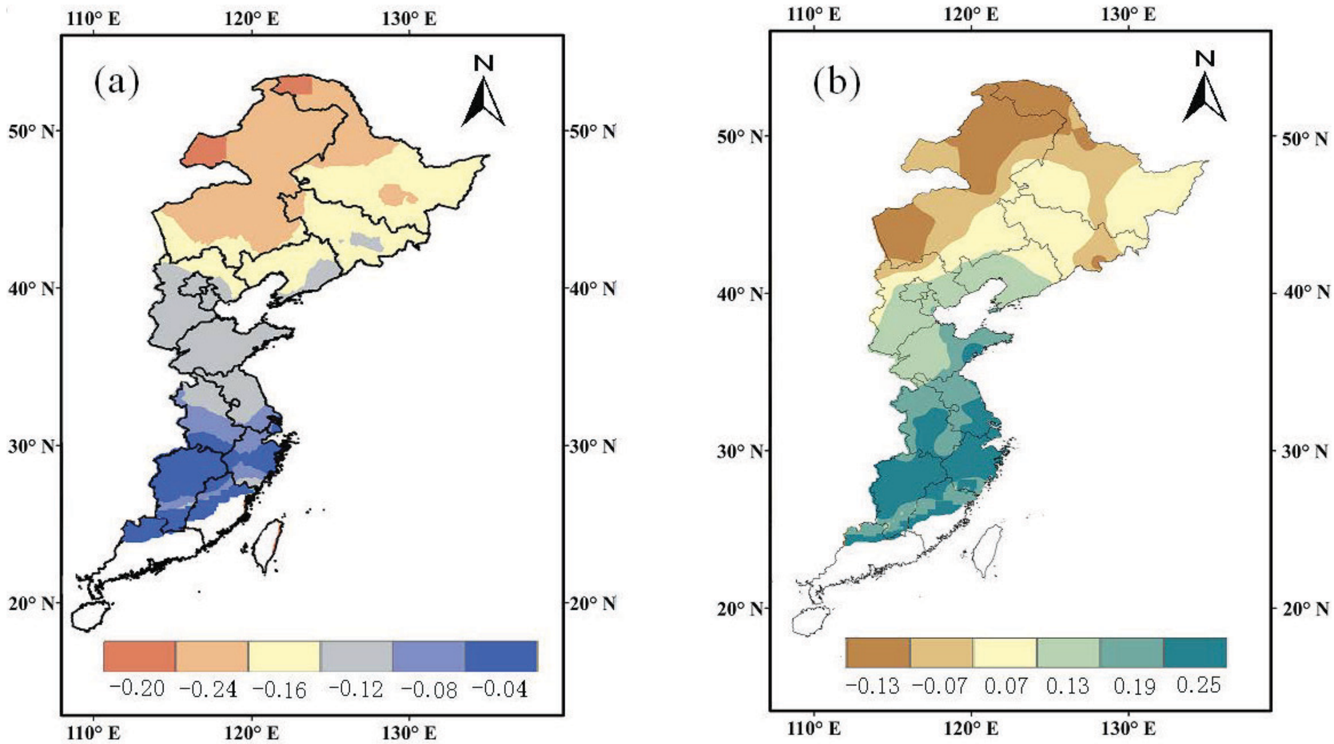

FIGURE 3. The first two eigenvectors of the EOF decomposition of the first date of ≤0 °C temperature: (a) first eigenvector, (b) second eigenvector.

Wang et al., 2011a) and caused the delay in the first date of ≤0 °C temperature from the south to the north. As shown in Figure 6, the annual average first date of ≤0 °C temperature occurred on 15 November at 33°N in southern areas, and between 6 October and 14 November at 33°N–42°N, between 16 September and 5 October at 43°N–48°N, and in mid-September at 48°N in northern areas. In addition, after the 1980s, the first date of ≤0 °C temperature was delayed significantly at the 48°N southern area; indeed ≤0 °C temperature did not occur in the 25°N southern area. These findings confirm the existing results, which find that the average early frost appeared on October 22, and since the 1990s the early frost has been late (Cheng, 2011; Du et al., 2011). Furthermore, the variations in the first dates of ≤0 °C temperature are mainly caused by climate change affecting the rise in the daily minimum temperature (Qian and Qin, 2006).

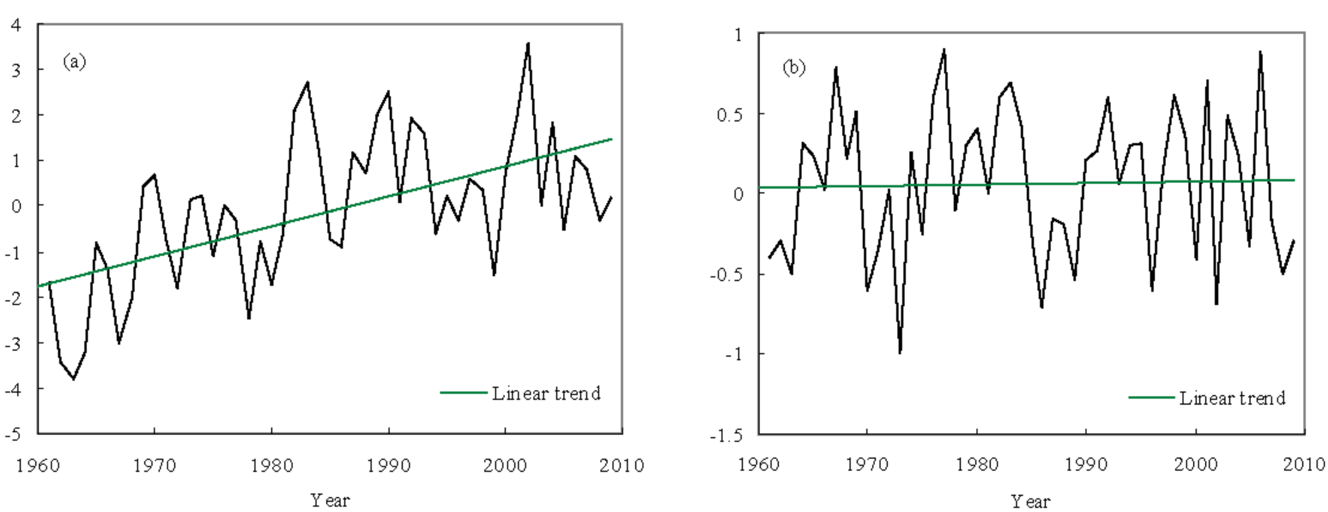

FIGURE 4. The time coefficient of the empirical othogonal function (EOF) decomposition of the first date of ≤0 °C temperature: (a) first eigenvector, (b) second eigenvector.

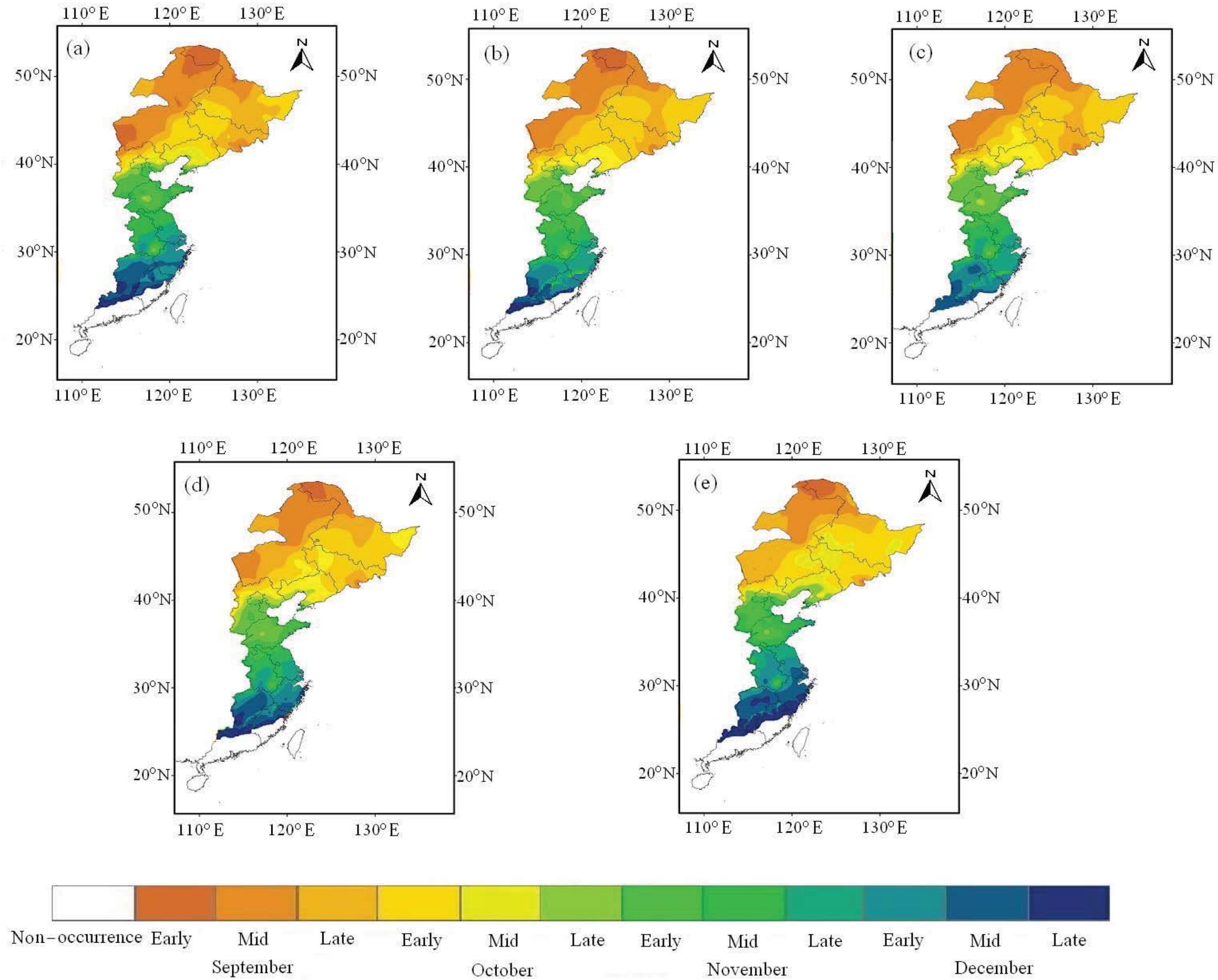

FIGURE 5. The distributions of the first date of ≤0 °Ctemperature at different time periods: (a) 1960s, (b) 1970s, (c) 1980s, (d) 1990s, (e) 2000s.

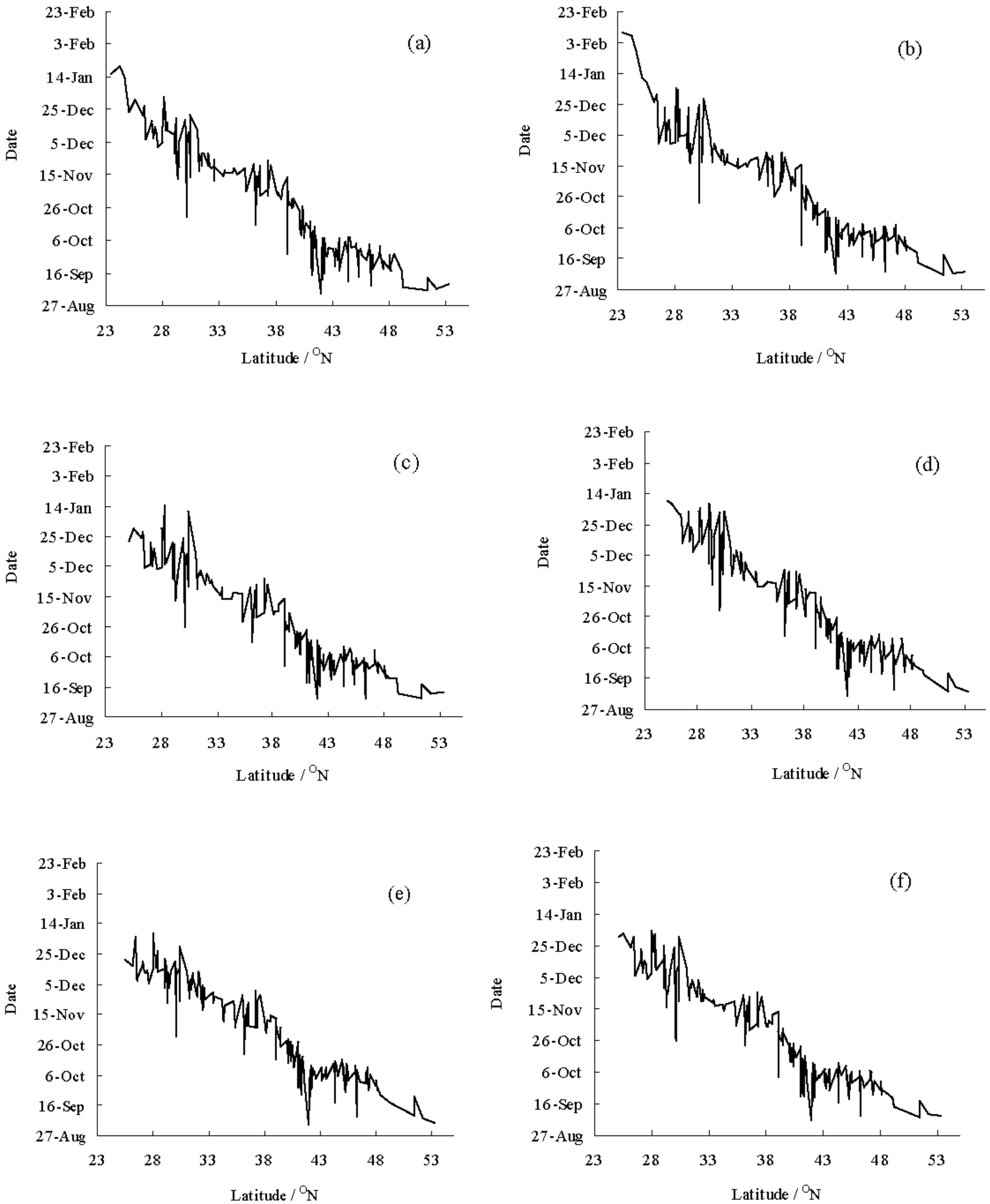

FIGURE 6. The changes in the first date of ≤0 °C temperature within latitude at different time periods: (a) 1960s, (b) 1970s, (c) 1980s, (d) 1990s, (e) 2000s, (f) annual average.

It can be seen from Figure 7 that the average standard deviation of the first date of ≤0 °C temperature in East China has regional differences. In the north, the interannual variation of the first date of ≤0 °C temperature is small, whereas in the south it is large;

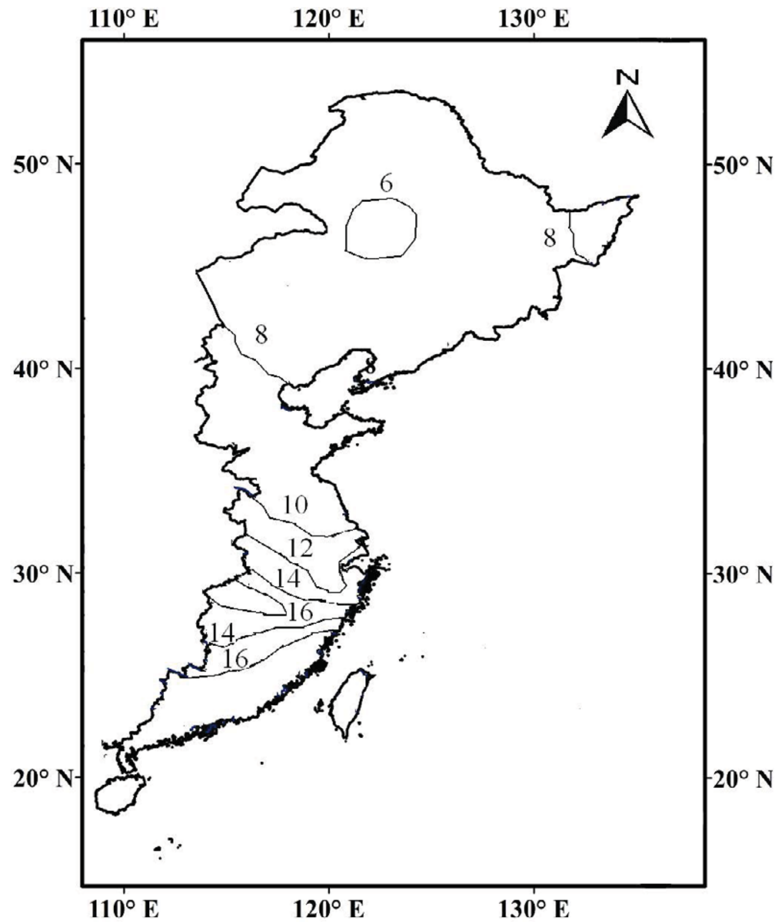

FIGURE 7. The spatial distribution of the standard deviation of the first date of ≤0 °C temperature.

it was 6.73–8.25 in the north, 10.81–12.29 in intermediate areas, and 13.21–17.42 in southern regions. These changes illustrate that the extent of interannual variability of the first date of ≤0 °C temperature was greater at low latitudes, while stability was relatively poor. Conversely in areas of high latitudes the scope of change was small, while relatively, stability was better.

As can be seen from Figure 8, in September, October, November, and December, the first date of ≤0 °C temperature displays a rate of delay of 1.2 days per 10 years, 1.5 days per 10 years, 1.5 days per 10 years, and 2.0 days per 10 years, respectively. From 1960–1985, the first date of ≤0 °C temperature was early during the middle of September and then was clearly delayed. In October before 1995, the first date of ≤0 °C temperature fluctuated, and then it was delayed. In November and December from 1961–1995, the first date of ≤0 °C temperature was early and was delayed afterward. This indicates that the first date of ≤0 °C temperature was early between 1960 and 1980, but thereafter it was delayed significantly. Since the 21st century, the average first date of ≤0 °C temperature date has been delayed by 5–7 days more than between the 1960s and1990s. Overall, from the 1990s to present, it has displayed a lengthening trend.

According to the daily minimum temperature distribution and geographical environment, East China can be divided into two parts, north and south, with the boundary at about 39°N. It can be seen from Figure 9 that the first date of ≤0 °C temperature was 7 days earlier in the north between 1960 and 1995, and was 12 days earlier in the south. In the north, since the mid-1990s, the first date of ≤0 °C temperature has evidently been delayed by 8 days, whereas this number reached 14 days in the south; moreover the change in the south was greater than that in the north. These results confirm findings reported by Du et al. (2011) and Wang et al. (2009).

THE TIME VARIATION CHARACTERISTICS OF THE FIRST DATE OF ≤0 °C TEMPERATURE

It can be seen from Table 1 that the annual average first date of ≤0 °C temperature occurs on 30 October. For September, October, November, and December, the first date of ≤0 °C temperature appeared mainly in the last third of the month, early third of the month, middle third of the month, and middle third of the month, respectively. It can be seen from Figure 10 that it has the highest frequency in October, the second highest in November, and the lowest in September; however, in September and November the frequency decreased, whereas it increased in October and December. Furthermore, since the 1980s in particular, the change has been significant. It can be seen from Figure 11 and Table 1 that, in general, the average first date of ≤0 °C temperature has presented a trend of being delayed in the past 50 years in East China, at a rate of about 1.6 days per 10 years. However, prior to the 1990s, it showed a trend of arriving early and then a trend of being delayed. Between 1961 and 1970, the first date of ≤0 °C temperature was clearly early, and between 1971 and 1990 it fluctuated before becoming delayed. The average tendency of –1.8 days per 10 years was presented between the 1960s and 1990s, but since the 1990s the climate tendency reached 3.3 days per 10 years. In the 1960s, 1970s, 1980s, 1990s, and 2000s, the average first date of ≤0 °C temperature respectively appeared on 28 October, 29 October, 31

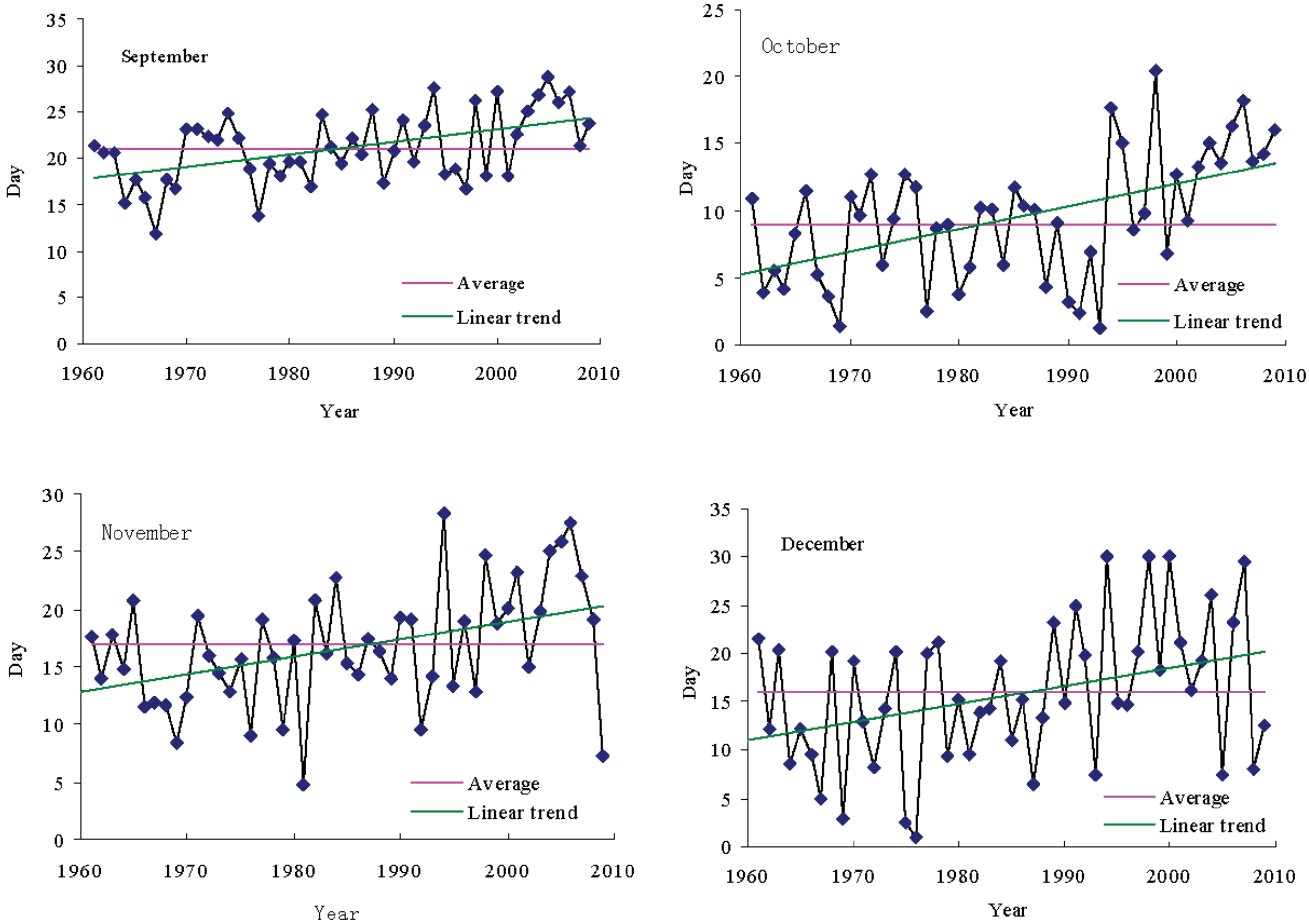

FIGURE 8. The change of the first date of ≤0 °C temperature in different months.

October, 2 November, and 4 November, and the respective trend rate was –2.9 days per 10 years, –1.7days per 10 years, –0.6 days per 10 years, 2.7 days per 10 years, and 3.9 days per 10 years; moreover, they all passed the 0.01 significance test.

Through calculating the linear trend value of the first date of ≤0 °C temperature by using the interpolation and the natural break point law, its spatial trend in East China is shown in Figure 12. It can be seen that variations in the first date of ≤0 °C temperature in the past 50 years showed a trend of being delayed in most areas. The most evident areas where delays have occurred were located west of Hebei and Tianjin, north of Jiangxi, and south of Anhui Province; moreover the trend rate reached 3–5 days per 10 years. There was only a slight trend

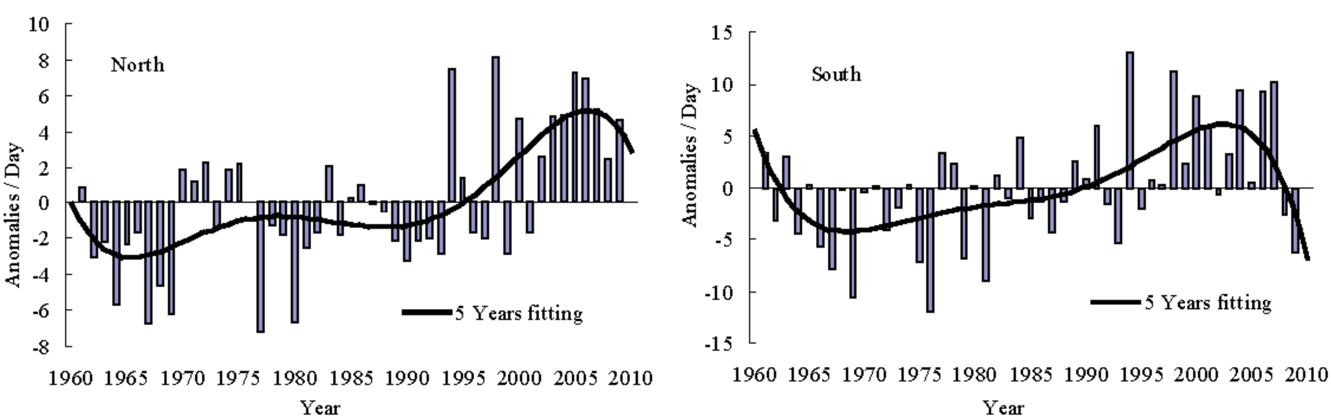

FIGURE 9. Anomalies in the changes of the first date of ≤0 °C temperature.

TABLE 1

The date and change rate of the first date of ≤0 °C temperature in different time periods.

	Occurrence date (month/date)					Change rate (day/10 years)			
	September	October	November	December	Average	September	October	November	December
1961–1970	9/19	10/7	11/15	12/14	10/28	–3.3	–3.6	–2.3	–2.3
1971–1980	9/21	10/9	11/16	12/13	10/29	–1.1	–1.6	–1.3	–3.2
1981–1990	9/21	10/11	11/17	12/15	10/31	–0.7	–0.1	–0.3	–1.2
1991–2000	9/23	10/13	11/19	12/23	11/2	0.5	2.0	1.6	6.7
2001–2009	9/25	10/15	11/21	12/22	11/4	3.2	4.1	4.2	4.0
Average	9/21	10/9	11/17	12/16	10/30	1.2	1.5	1.5	2.0

of this temperature arriving early, at a rate of 1–2 days per 10 years, in smaller areas, which were mainly located in certain areas, including Mohe in the Heilongjiang province, the north of Inner Mongolia, and the west of Shandong province. Delays in the first date of ≤0 °C temperature are mainly caused by climate change affecting the daily minimum temperature rise (Qian and Lin, 2004; Zhai and Pan, 2003). Through analysis, it was found that the more acute examples of areas where postponement occurs are related to high temperature cities such as Anshan in Liaoning; Zhangjiakou in Hebei; Longkou in Shandong; and Beijing, Jingdezhen, and Guixi in Jiangxi; this is consistent with the findings of Cheng (2011) who stated that the date of an urban early frost was later than that of the countryside, whereas the final frost date in urban areas was earlier than that of the countryside; this reflects the characteristics of the tropical island effect.

THE EFFECT ON FARMING OF THE FIRST DATE OF ≤0 °C TEMPERATURE

Figure 13 displays the trends relating to the end date of ≤0 °C temperature. This figure clearly shows that the end date of ≤0 °C temperature has been getting earlier at a rate of 3 days per 10 years; in particular it has been 10 days early since the 1990s. The sustained days of ≤0 °C temperature from beginning to end have shortened at a rate of 5 days per 10 years in East China (see Fig. 14), which means that delays in the first date of ≤0 °C temperature will lead to an early frost and a shortening in the length of frosty periods; therefore the delayed date of ≤0 °C temperature would lead to changes in the climate and guide agricultural production. Because the continuous days of ≤0 °C temperature decreased, the accumulated >0 °C temperatures will increase, which is conducive to crop production. As can be seen from Figure 15, the days of ≤0 °C temperature and crop yields showed a significant positive correlation, with the correlation coefficient being +0.4749 and confidence levels being reached. Moreover, when the first date of ≤0 °C temperature was delayed, the crop yield increased. In the higher latitude northern region (Jilin, Heilongjiang, and Liaoning) there were clear changes to the level of planting: for example, products such as winter wheat and oilseed crops increased by 10.2% per 10 years and 17.2% per 10 years, respectively. Wang et al. (2011b) and Zhao et al. (2010) had found that in the north of Eastern China, the climate was relatively cold and the frosty periods were long, which were not conducive to cultivating a large number of crops. However, the results here indicate that with a delay in the first date of ≤0 °C temperature leading to a shortening of frost periods, it would be possible to plant crops that were not previously cultivated in some regions, and simultaneously also provide conditions in which the number of crop

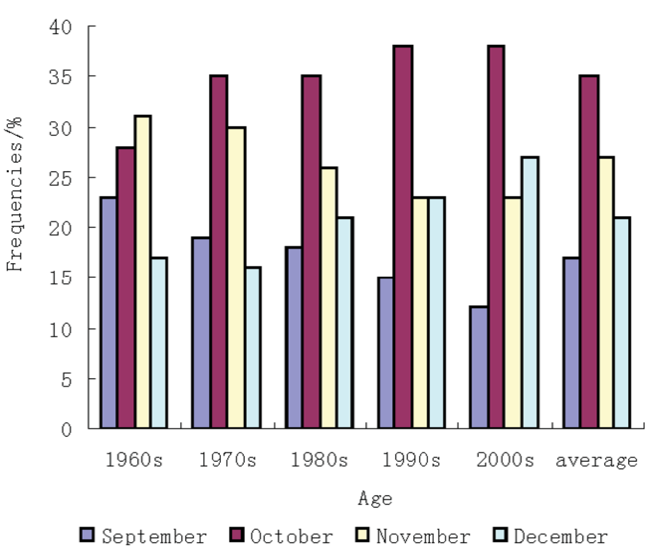

FIGURE 10. The frequencies of the first date of ≤0 °C temperature in different ages.

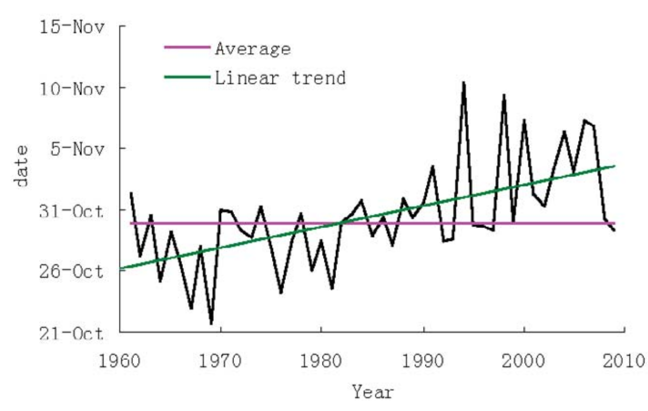

FIGURE 11. The annual average change of the first date of ≤0 °C temperature in East China.

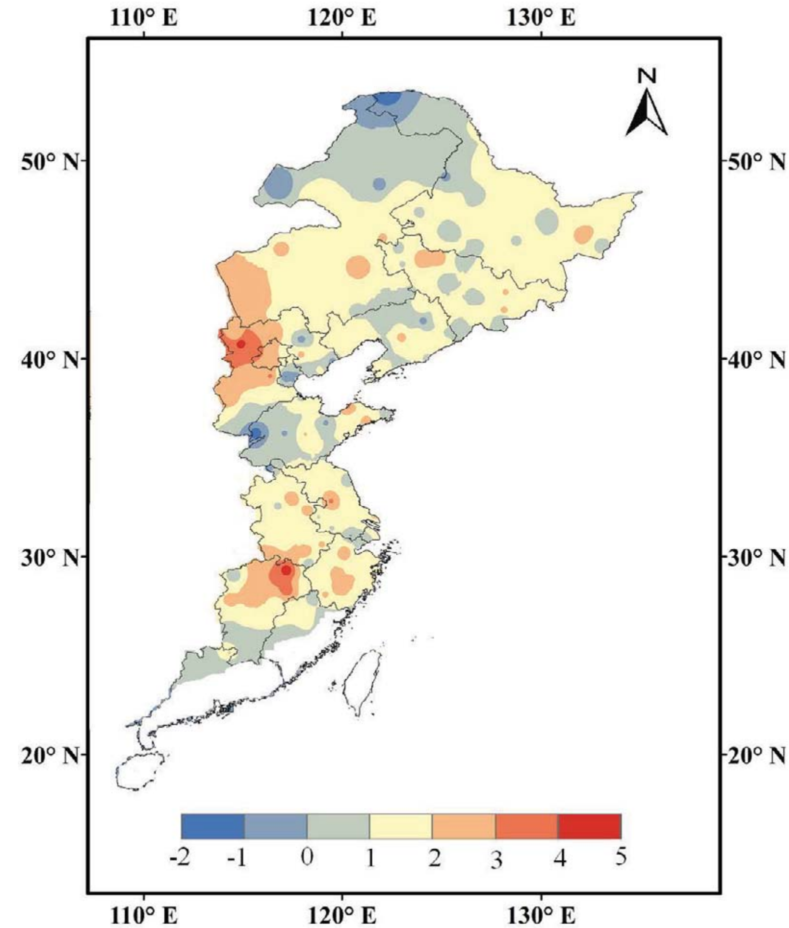

FIGURE 12. The spatial trend distribution of the first date of ≤0 °C temperature. Unit: days/10 years.

varieties could be increased and thereby the structure of farming adjusted. However, due to the increased heat in some areas, the chance of pests and diseases would increase and lead to a drop in grain yield. Therefore it is necessary to plan for a reasonable utilization of climate resources, while avoiding any associated disadvantages; thereby revenue can be maximized. The results therefore reveal that the first date of ≤0 °C temperature has a significant effect on the length of frosty periods and farming.

Conclusions

In this study, trends relating to the change of the first date of ≤0 °C temperature in East China and its effects on farming have been analyzed. The following conclusions can be drawn from this analysis:

(1) The average first date of ≤0 °C temperature displayed a trend of being delayed in East China with the trend rate being larg-

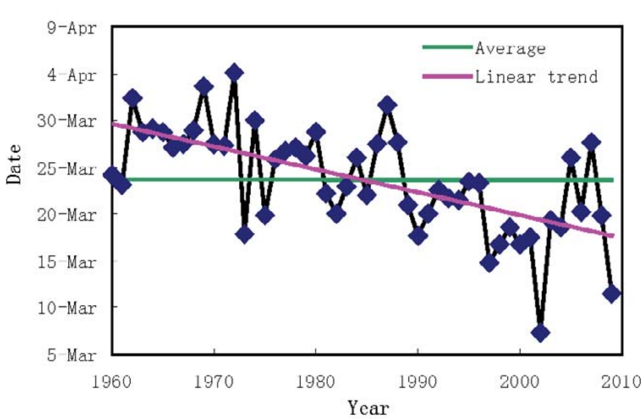

FIGURE 13. The annual average change of the end date of ≤0 °C temperature in East China.

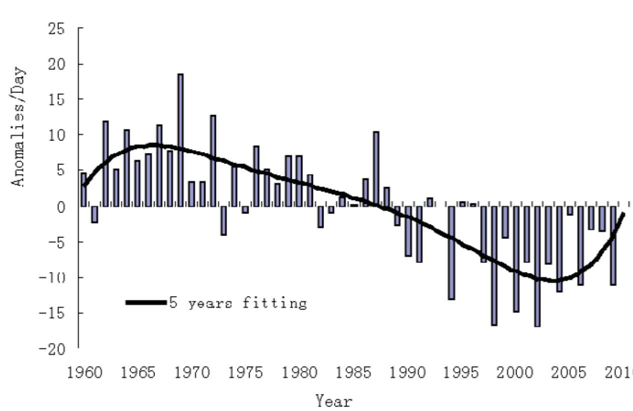

FIGURE 14. Anomalies in the changes of the sustained days of ≤0 °C temperature from beginning to end in East China.

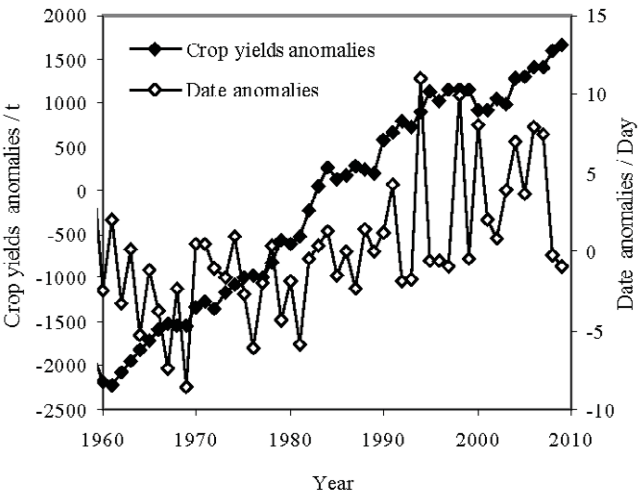

FIGURE 15. The changes in crop yields and the first date of ≤0 °C temperature date in East China.

est in December. The interannual variation of the first date of ≤0 °C temperature is greater at low latitudes, and smaller at high latitudes. Those areas where there is a significant delay are generally high temperature cities.

(2) The distribution boundaries of the first date of ≤0 °C temperature moved from south to north between September and December; this has been particularly evident since the 1990s. Furthermore, ≤0 °C temperature did not even occur in certain southern stations.

(3) Trends related to the first date of ≤0 °C temperature are relevant to the daily minimum temperature rising and climate warming. A delay in the first date of ≤0 °C temperature leads to frost periods shortening and suitable conditions for increasing the number of crop varieties and adjusting the structure of farming.

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