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Impact of rapid Arctic sea ice decline on China's crop yield under global warming

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Abstract
Food is the material basis for human survival. Therefore, food security is a top priority for the people's livelihood and the sustainable development and future destiny of human beings. In the context of global warming in recent decades, the Arctic region has experienced more significant temperature anomalies than the midlatitudes due to the "Arctic amplification," and the rate of sea ice reduction has accelerated, which has an important impact on climate change in the middle and high latitudes, especially the frequent occurrence of extreme climate disasters that seriously affect food security and China's agricultural production. However, little research has been conducted on the role of changes in this important system of Arctic sea ice in China's agricultural production. Therefore, this paper analyzes the interannual variability and multi-year trends of Arctic sea ice concentration, CO2, air temperature, precipitation and China's major crop yield data to explore the possible effects and mechanisms of the rapid decrease in Arctic sea ice on China's grain production. From the analysis, it was found that the yield of major grains (rice, maize, wheat and soybean) in China was closely related to the Arctic sea ice anomaly in the previous summer and autumn, and the influence process was primarily through the dynamic process of the Arctic sea ice anomaly affecting the meridional temperature gradient and the positive and negative Arctic Oscillation phases, which in turn affected the air temperature anomalies in Eurasia and China, and finally led to the anomalous changes in Chinese grain yield. Based on this, a prediction model of China's major grain yield was established by stepwise nonlinear multiple regression analysis, which is a good fit and is expected to increase China's major crop yield by 11.4% in 2022 compared with last year. This presents new ideas and methods for future grain yield assessment in China and has far-reaching guidance for the stability and development of national and regional economies worldwide.

Keywords Arctic sea ice · Arctic Oscillation (AO) · Crop yield · Nonlinear multiple regression

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1 Introduction

The Arctic is the most sensitive region in terms of global climate change response (Dyurgerov & Meier, 2000; Rye et al., 2010), acting as an indicator and amplifier of climate change (Barry et al., 1993; Comiso, 2002; Dickson, 1999; Overland et al., 2014; Rigor et al., 2002; Rothrock & Zhang, 2005), and although Arctic sea ice covers only a small fraction of the global ocean area, it plays a very important role in the overall Earth system (Bader et al., 2011). The unique amplifying effects of the Arctic (Screen & Simmonds, 2010; Serreze & Barry, 2011) have not only accelerated Arctic warming, sea ice melt and high temperature, but have also led to frequent extreme events at midlatitudes (Cohen et al., 2014). Worryingly, over the past 30 years, Arctic temperatures have increased twice as fast as the global average as global warming has intensified. According to the US National Snow and Ice Data Center, the polar sea ice area in July 2020 will be the smallest in 40 years (Liang et al., 2022). A recent study predicts that the Arctic Ocean could experience complete sea ice melt every summer beginning sometime between 2044 and 2067 due to anthropogenic climate change (Thackeray & Hall, 2019).

The Arctic amplification effect not only affects the Arctic region but also has an important impact on the weather and climate in midlatitudes (Cohen et al., 2014; Screen & Simmonds, 2013). The decrease in temperature gradient between the Arctic and midlatitudes following Arctic warming leads to an increase in positive atmospheric pressure, which is prone to anomalous climate changes and extreme weather occurrences at mid- and high latitudes (Francis & Vavrus, 2012; Screen & Simmonds, 2014). In turn, the anomalous changes in local climate and the frequent occurrence of extreme weather will undoubtedly have important implications for China's agricultural production and food security (Powell & Reinhard, 2016; Tirado et al., 2010), which can be summarized mainly in positive and negative aspects.

From the positive aspect, firstly, local climate anomalies cause significant changes in temperature extremes and prolong the growing season of crops, especially in the midlatitudes where the start date of the suitable growing season is earlier, and the end date is later, resulting in an extension of the growing season of crops in these areas and a shift of the cropping belt northward and an increase in yield (Duzheng et al., 2003; Yang et al., 2007). Secondly, the change in thermal conditions may also reduce the low temperature and cold damage and increase the area of late-maturing crop varieties (Li et al., 2022). Besides, CO2 is an essential element of crop photosynthesis and a major climate change scenario construction indicator. Increasing CO2 concentration in the Earth's atmosphere can increase the photosynthetic rate of crops, which directly stimulates crop growth and increases the dry matter content, resulting in increased food production (Lawlor & Mitchell, 1991; Wang et al., 2014b; Ziska & Bunce, 2007).

On the negative side, the frequency of extreme weather and climate events such as drought, heavy rainfall, high temperature, extreme cold and heavy snowfall has increased in frequency and intensity, all of which have significant losses on food production (Huang et al., 2014). Although climate change may lead to increased precipitation in some parts of China, the increased evaporation of water will still eventually reduce effective soil moisture, leading to drought-related crop yield reduction (Hatfield & Dold, 2019; Morison et al., 2008). Moreover, local climate change itself also has an impact on crop growth and production quality. Without new adaptation technologies, the crop reproductive period will be shortened, which will offset the effects of a longer year-round crop growing period and thus have an impact on crop yields (Gornall et al., 2010).

However, as we mentioned, previous work either has been focused on the impact of Arctic sea ice on midlatitude climate or has been interested in the general and macroscopic topic of how "climate change" affects food security. However, little research has been done on the role of changes in Arctic sea ice on Chinese agricultural production in the context of global warming and even less on the mechanisms of this impact. Because of this, our work will attempt to bridge this knowledge gap, i.e., to investigate the possible effects of Arctic sea ice changes on China's grain production under global warming, as well as to explore the possible mechanisms between them and establish a forecast model to predict the future trend of China's major grain yield. This is an important reference for the formulation of national agricultural development strategies and food security development plans in response to climate change and for maintaining regional and social stability.

2 Data and methodology

2.1 Data

We used monthly average temperature and precipitation data collected from the National Climate Center for 160 weather stations in China from 1961 to 2021 (http://cmdp.ncc-cma.net/). The Food and Agriculture Organization of the United Nations (https://www.fao.org/faostat/en/#data/QCL) provided information on the yields of China's four major crops, including rice, maize, wheat and soybean, from 1961 through 2020. In addition, we used SST and global sea ice concentration data from 1951 to 2020 from the Hadley Center (https://www.metoffice.gov.uk/hadobs/hadisst/). The monthly Arctic Oscillation (AO) index is available from NOAA's Climate Prediction Center (ftp:/ftp.cpc.ncep.noaa.gov), and CO2 data from Mauna Loa and other global sampling sites may be discovered via the GML Data Finder of open data sets in the Global Monitoring Laboratory (https://gml.noaa.gov/ccgg/trends/data). The Siberian High-Pressure Index comes from the National Climate Center of China Meteorological Administration, which selects the average location of Siberian high-pressure climate, calculates the average sea level pressure value in the region and standardizes it (http://cmdp.ncc-cma.net/Monitoring/monsoon.php).

2.2 Variables

2.2.1 Annual mean temperature anomaly (ATA)

The annual mean temperature is the average temperature of the four seasons, which is valuable data that can assess an area's climate change (Wang et al., 2014a) and the anomaly means a departure from the climate normal.

2.2.2 Land surface temperature anomaly (LSTA)

Land surface temperature is the radiative skin temperature of the land derived from solar radiation (Jamali et al., 2022), and the anomaly is a description of how the temperature of the surface of the Earth deviates from the average.

2.2.3 Sea surface temperature anomaly (SSTA)

Sea surface temperature is the temperature of the top millimeter of the ocean surface (Stock et al., 2015). Anomalies are deviations from average conditions relative to the climatological normal.

2.2.4 Arctic sea ice concentration (ASIC)

Arctic sea ice concentration is defined as the area of arctic sea ice relative to the total at a given point in the ocean, which is a useful variable for assessing sea ice variability (Deser & Teng, 2008).

2.2.5 Arctic Oscillation (AO) index

The Arctic Oscillation (AO) is a climate index of the state of the atmospheric circulation over the Arctic (Aanes et al., 2002).

2.2.6 Siberian High

The Siberian High is a massive collection of cold and dry air that accumulates in the northeastern part of Eurasia, which is the strongest semipermanent high and affects most weather patterns in the northern hemisphere (Cohen et al., 2001).

2.2.7 East Asian monsoon

The East Asian monsoon is an important part of the Asian monsoon, and its movement and change affect the weather and climate in China (Ha et al., 2012).

2.3 Methodology

2.3.1 Nonlinear regression analysis

Nonlinear regression is a method of finding a nonlinear model of the relationship between a dependent variable and a set of independent variables and can estimate models with any relationships between the independent and dependent variables (Milliken, 1990). Our research used this approach to investigate the potential connection among grain yield, ASIC, CO2, air temperature and other factors.

2.3.2 Time-lagged correlation analysis

Time-lagged correlation usually refers to the correlation between two-time series shifted relatively in time. The analysis quantifies how synchronized two-time series is by computing the correlation between them for different time shifts (D'haeseleer et al., 1998; Moews et al., 2019; Schmitt et al., 2004). Here we used this method to further understand whether the Arctic sea ice affects the air temperature in China through the change of AO.

2.3.3 Stepwise multiple nonlinear regression analysis

It is a statistical technique that can be used to analyze the relationship between a single dependent variable and several independent variables (Abdul et al., 2005), which is a reliable approach for choosing the best subset models or the ideal arrangement of independent variables (Cevik, 2007). In order to predict crop yield, we adopt the stepwise multiple nonlinear regression method to analyze and screen the factors linked to changes in the Arctic sea ice.

2.3.4 Coefficient of determination

The coefficient of determination (*R*-squared) is a statistical measurement that assesses how strong the relationship is between two variables in the regression equation (Ozer et al., 1985). Our study uses this approach to evaluate the strength of the relationship among crop yield, ASIC, CO2, air temperature and other variables.

3 Results and discussion

3.1 China's grain yields and climate change characteristics

To gain a picture of the long-term global climate change characteristics in the context of global warming, we show the global annual mean temperature anomaly (ATA), land surface temperature anomaly (LSTA) and sea surface temperature anomaly (SSTA) from 1850 to 2021 (Fig. 1a). For comparative analysis, the annual ATA in China is also given for 1951–2021. Figure 1a shows that the trends of global ATA, LSTA and SSTA are basically the same from 1850 to 2021, with apparent interannual variability characterized by a significant upward trend, and the 1980s is the dividing line of the sudden change in temperature rise. While the oscillation amplitude of global ATA and SSTA is identical, the global ATA is slightly lower (or the same) than SSTA before the abrupt change. There is a reversal after that where SSTA is lower than ATA. The oscillation amplitude of global LSTA is more significant than that of ATA and SSTA. Before the abrupt change, the LSTA is lower than the ATA and SSTA, while after the abrupt change, the LSTA is significantly higher than that of ATA and SSTA. Besides, we find that the amplitude of the ATA change in China is significantly larger than global ATA, LSTA and SSTA.

We have made a statistical analysis of rice, maize, wheat and soybean yields in China and shown the change curve from 1961 to 2020. Figure 1b shows that the crop yield trend in China is rapidly increasing. Although rice and maize yields fluctuated significantly, they quickly increased yearly, whereas soybean yields grew relatively slowly.

Previous findings suggest that local air temperature and precipitation are important climatic factors affecting crop growth and yield (Högy et al., 2013; Kang et al., 2009; Lobell et al., 2007). To understand the relationship between China's crop yield and local air temperature, precipitation and global CO_2, we analyzed the characteristics of annual mean air temperature, precipitation and global CO_2 variability. Figure 2 shows the variation anomalies of annual mean temperature, precipitation in China and global CO_2. Both temperature

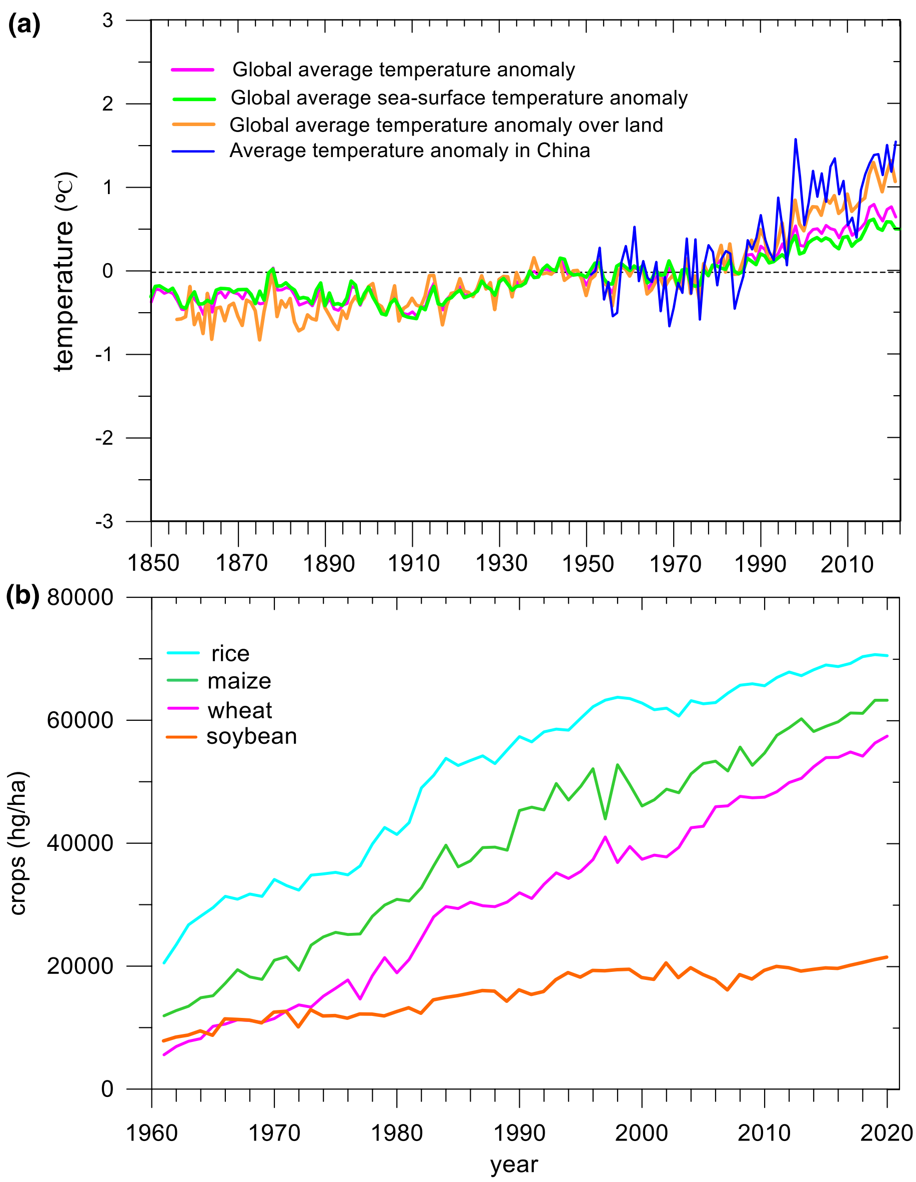

Fig. 1 **a** Global annual average temperature anomalies (SSTA, green; LSTA, yellow) from 1850 to 2021; ATA in China (blue) from 1951 to 2021; Anomalies are defined relative to the 1961–1990 average. **b** Major crop yield in China

and precipitation in China have prominent annual and interannual variation characteristics. Before the 1990s, the temperature anomaly basically fluctuated about 0.5 °C, but after the 1990s, the temperature increased significantly with the highest anomaly reaching 1.7 °C despite fluctuations. The change of global CO_2 is increasing year by year, which is consistent with the trend of temperature change. The rapid rise in temperature across China

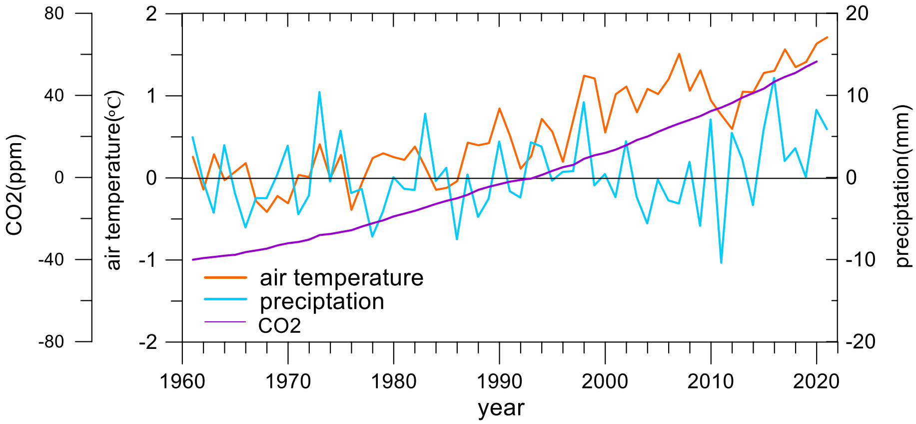

Fig. 2 Long-term variation of global average CO_2 anomaly, air temperature anomaly and precipitation anomaly in China

is consistent with the rate of global warming (Ding et al., 2014). Precipitation in China is different from temperature and global CO_2. Although there is an apparent interannual variation of precipitation, there is no obvious increasing trend. By comparing Figs. 2 and 1, it can be found that China's air temperature and global CO_2 change have the same trend as crop yield. This paper will focus on the impact of Arctic sea ice and its related meteorological factors as well as global CO_2 and air temperature changes in China on Chinese crop yields.

As shown by the previous study, Arctic sea ice has a significant annual variation characteristic of winter–spring freezing and summer–fall melting, especially since 1980, the reduction in summer sea ice area of Arctic sea ice is equivalent to 40% of the area of the USA (Francis et al., 2021). The relevant analysis indicates that summer–fall Arctic sea ice has been a consistently negative anomaly since 2000, and then, Arctic sea ice has been even further below the climate average since 2004 (Francis & Vavrus, 2012). Such a rapid decrease in summer–autumn Arctic sea ice is bound to have an important impact on the global climate. For this reason, this paper selects summer–autumn Arctic sea ice for China's crop yield analysis.

3.2 The linkage between Chinese grain yield and Arctic sea ice

Figure 3a shows the scatter diagram of Arctic sea ice and Chinese crops (rice, maize, wheat and soybean) yield in China. It can be seen that there is a very significant nonlinear negative correlation between Arctic sea ice and different kinds of crop yield in China since the coefficient of determination (R-squared) is 0.85, 0.88, 0.88 and 0.75, respectively. The results of this analysis indicate that there is a definite and nonlinear relationship between crops yield and Arctic sea ice in China.

It has been shown that an important cause of global warming is related to the continuous increase of greenhouse gases such as CO_2 (Jenkinson et al., 1991; Norby & Luo, 2004), and the rapid decrease of Arctic sea ice should have some connection with CO_2. Therefore, CO_2 should have the same effect as Arctic sea ice on crop yield in China. Figure 3b shows the scatter diagram of CO_2 and crop (rice, maize, wheat and soybean) yields in China. R-squared is 0.87, 0.92, 0.97 and 0.84, respectively. This

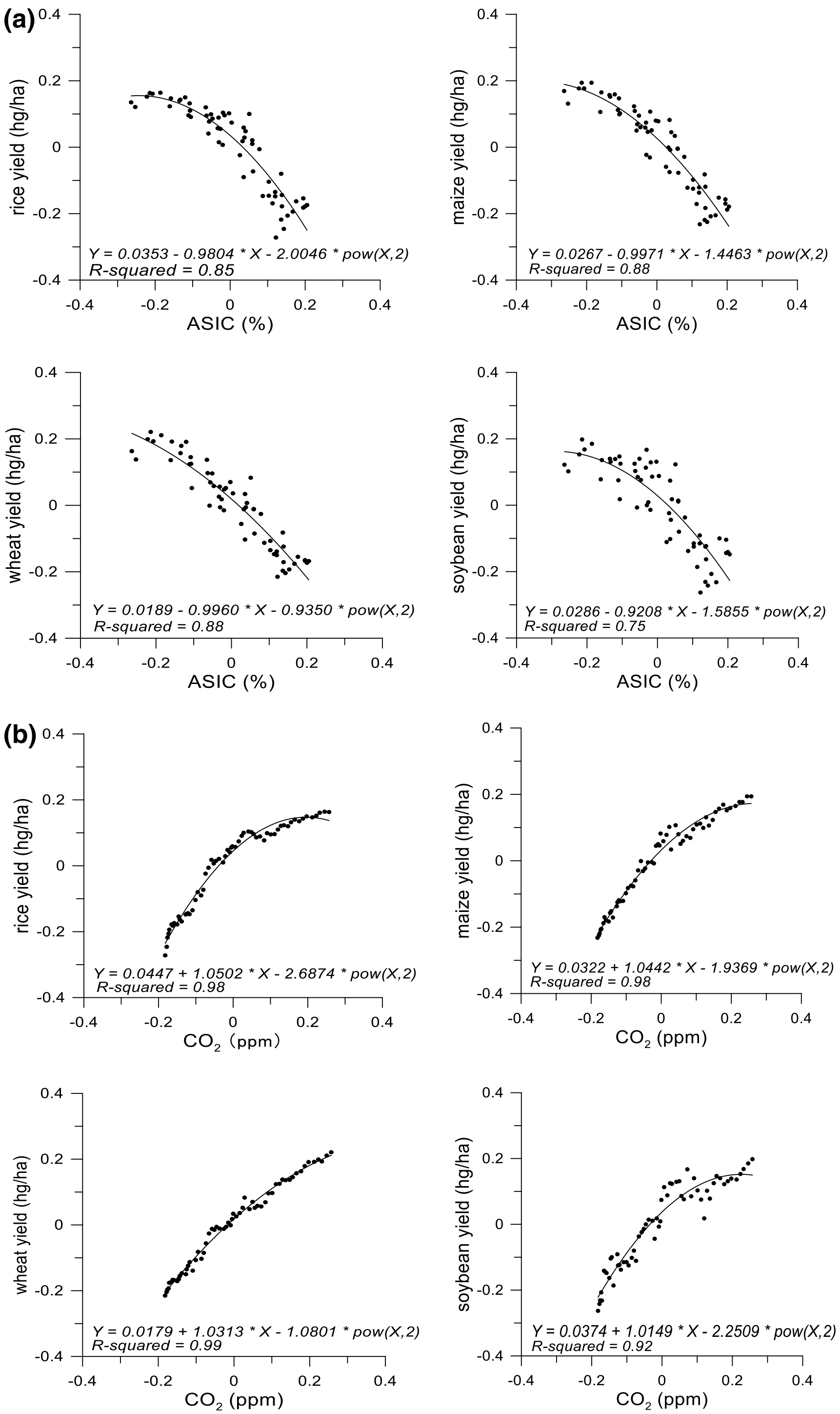

Fig. 3 Scatter diagram between crops yield and ASIC (**a**) and CO_2 (**b**) in China

result indicates that the relationship between crop yield and CO_2 in China is very close, with a nonlinear relationship.

3.3 Grain yield and local temperature variation in China

Under the influence of global warming, the yield changes of crops in China are also affected by local air temperature changes (Liu et al., 2013; Yang et al., 2011). Thus, we calculated the correlation field between rice yield and air temperature in seasons. Overall, there is a positive correlation between rice yield and air temperature in China. The air temperature of North China and Northeast in China and the middle and lower reaches of the Yangtze River are closely related to the current year's rice yield in winter and spring, especially in spring. The air temperature change in the winter and spring seasons is an important climatic condition for crop planting and growth, which is the key to ensuring crop yield. In summer, there are still good correlations in the Northeast and West (except Xinjiang) as well as South China and the southeast coast, but weak negative correlations appear in the Yellow River and Yangtze River basins, but they basically do not pass the 95% confidence level test. This suggests that relatively cooler temperatures in most southern regions in summer have a boosting effect on crop yield. In autumn, the harvest season of crops, there is a good correlation between air temperature and rice yield, and the air temperature in this season is the key to ensure rice yield. The correlation distribution between air temperature and maize yield in China is pretty similar to that for rice yield with a positive correlation, and maize yield is more correlated than rice yield in the Yellow River basin in autumn. The correlation distribution between wheat and air temperature is consistent with rice's situation. The air temperature mainly influences wheat growth in winter and spring. In particular, the Yellow River basin and the Yangtze River basin have a very significant influence. The correlation distribution between Soybean yield and air temperature in China is similar to that of rice yield and maize yield, but the correlation strength is relatively weaker.

Figure 4 shows the distribution of the correlation between the four major crops' yield average and temperature in China, and the correlation is very similar to the distribution of each kind of crop. In other words, the effect of local temperature on grain yield is exact and stable.

A scatter diagram (Fig. 5) is given for the average air temperature and crop yield in China to further analyze the relationship between air temperature and crop yield. There is a positive correlation between crop yield and air temperature in China. The R-squared given by the fitted connection between rice, maize, wheat and soybean and air temperature is 0.60, 0.63, 0.66 and 0.59, respectively; combined with the correlation coefficients between them ($r = 0.73$, 0.75, 0.78 and 0.74), it can be concluded that the correlation between them is still very close.

The above correlation analysis results indicate a close relationship between crop yield and local air temperature in China, and the abnormally high (low) air temperature in winter and spring determines the increase (decrease) in the crop yield in that year. For agricultural production, high and low air temperatures in winter and spring are necessary to ensure crop growth, while high and low air temperatures in summer and autumn are crucial to crop yield.

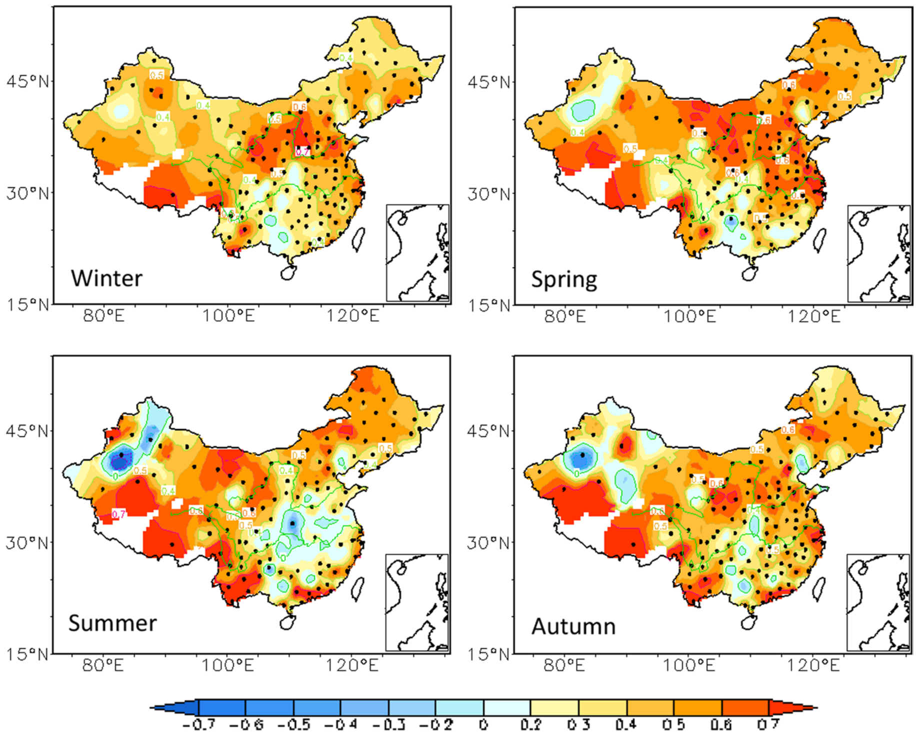

Fig. 4 Correlation between four major crops' yield average and the air temperature of the four seasons in China. The dots are statistically significant at the 95% confidence level

3.4 The ways in which Arctic sea ice affects China's crop yield

Figure 6 shows the spatial distribution of the correlation between the Arctic sea ice change in summer–autumn and the air temperature in China. It can be seen that the spatial distribution of Arctic sea ice change in the last summer–autumn is basically consistent with the effects of the four seasons in China, except for winter, and the highest correlation is with North China and the Yangtze River basin, followed by the northeast region. It can be seen from the curves of the multi-year average changes of Arctic sea ice and the average air temperature in China (Fig. 7) that there is a significant opposite phase relationship between them. There are significant interannual variations in both Arctic sea ice and China's air temperature, and both show abrupt changes after 1990, except that China's air temperature is rapidly increasing and Arctic sea ice is rapidly decreasing. Some previous works have concluded a similar relationship between Arctic sea ice and air temperature in China (Wu & Li, 2022; Zuo et al., 2016).

As an index of atmospheric circulation modes in the northern hemisphere, AO is a critical mode reflecting the longitudinal pressure gradient at mid–high latitudes that could make some contributions. To further understand whether the Arctic sea ice affects the air temperature in China through the change of AO in our study, we choose to analyze the Arctic sea ice and AO during 1951–2021, expecting to reveal the mechanism between them. Figure 8 shows the time-lagged correlation curves between Arctic sea ice and AO monthly.

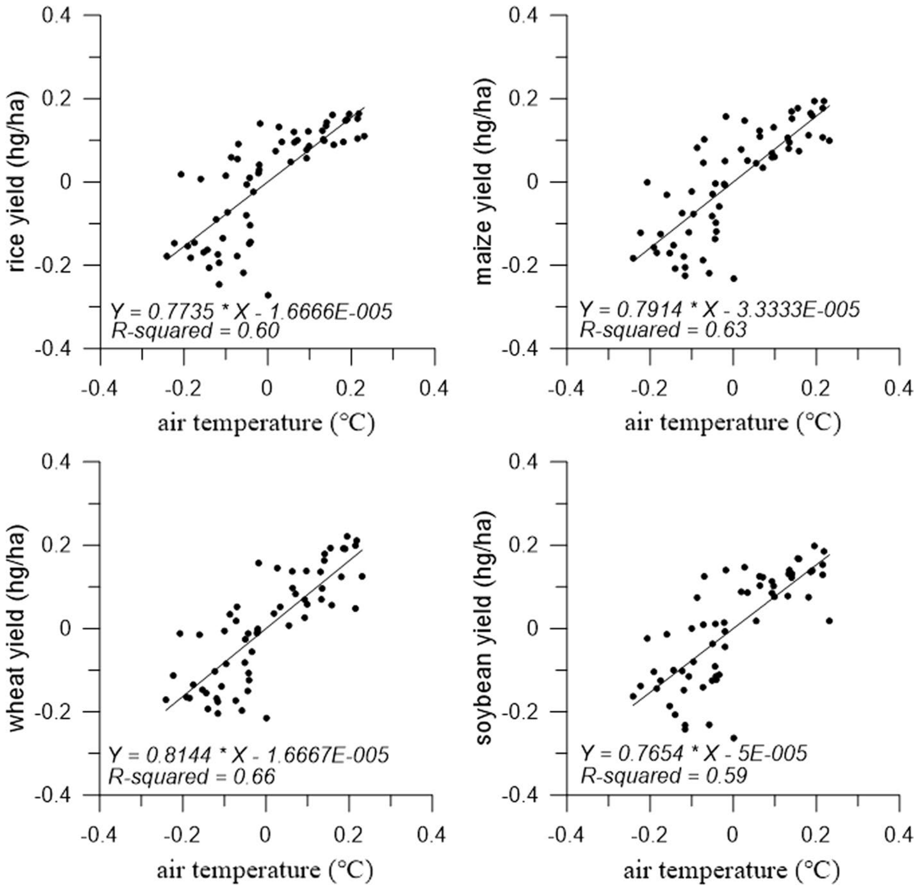

Fig. 5 Scatter diagram between air temperature (°C) and grain yield in China. The correlation coefficient of rice yield, maize yield, wheat yield and soybean yield are 0.73, 0.75, 0.78 and 0.74, respectively. The correlation coefficients all exceed a 99.9% confidence level

It can be seen that there is an obvious mutual influence process of AO on Arctic sea ice, and the most significant influence of AO on Arctic sea ice is when Arctic sea ice lags AO by 6–7 months, while the best correlation occurs when Arctic sea ice leads AO by 6 months. This result indicates that the interaction time between Arctic sea ice and AO is about one year.

AO is an important link to the atmospheric circulation at middle and high latitudes. Therefore, its positive and negative phases are important atmospheric modes that affect climate change at middle and low latitudes. We performed a correlation analysis between AO and Chinese air temperature, and found that the correlation coefficient between them is − 0.34, which exceeded the confidence level of 99.9%. This result indicates that a positive (negative) phase of the AO is associated with a trend of higher (lower) temperatures in China.

The results of the above analysis indicate that the key process of Arctic sea ice affecting the temperature in China is by influencing the positive and negative phases of AO, which in turn leads to the temperature change in China. The AO is the "bridge" between

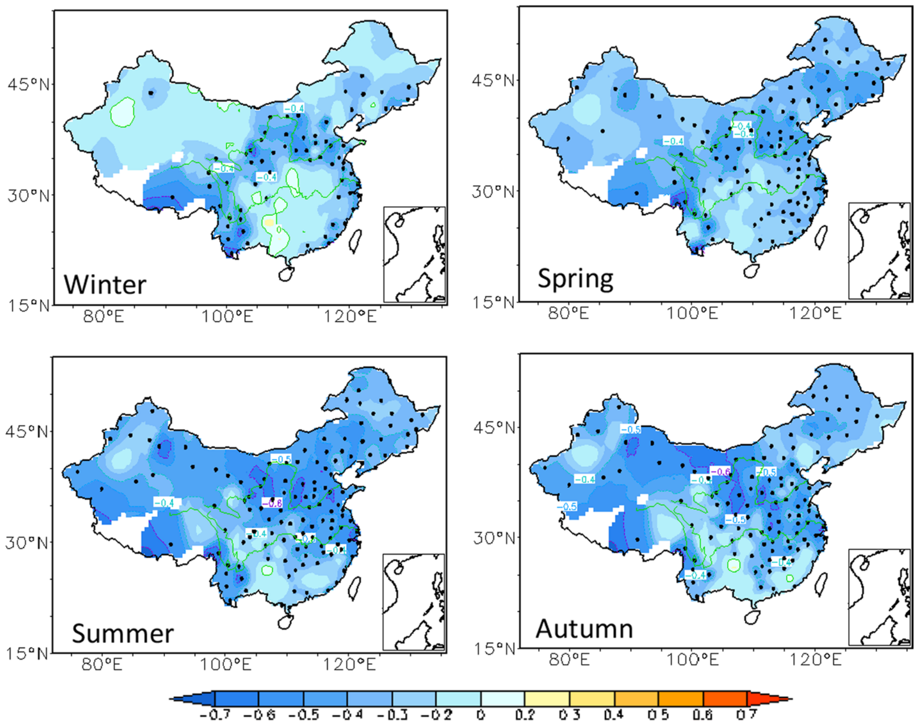

Fig. 6 Correlation between Arctic sea ice in the last summer–autumn and air temperature of the season in China. The dots are statistically significant at the 95% confidence level

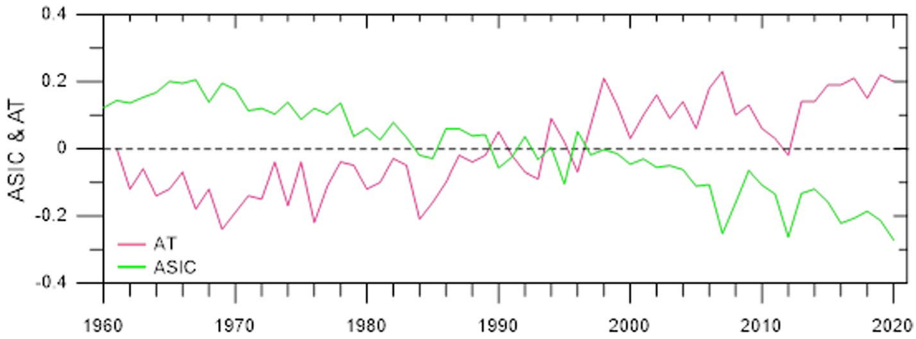

Fig. 7 Variation of the Arctic sea ice concentration (ASIC, green) and the air temperature (AT, red) in China. ASIC adopted the last summer–fall data; AT adopted annual mean data

the Arctic and midlatitude influence processes that ultimately affect the change of grain yield in China. This is consistent with previous findings (Nakamura et al., 2016).

It has been shown that the anomalous change of Arctic sea ice has an important influence on the winter air temperature in China, and the influence process is mainly the effect of the Arctic sea ice change on the East Asian winter monsoon intensity (Inoue et al., 2012). To investigate the relationship between Arctic sea ice and East Asian monsoon intensity, we used

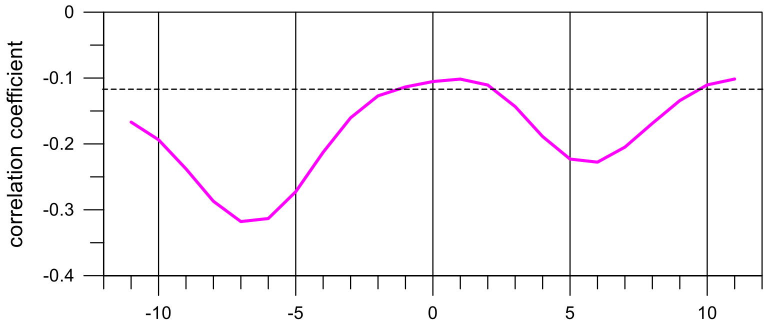

Fig. 8 Time-lagged correlation between monthly AO and ASIC from 1951 to 2021. ASIC$^-$ and ASIC$^+$ indicate ASIC leads AO and ASIC lags AO, respectively. The *x*-axis indicates lag time (months). The dotted line represents the correlation coefficient reached the 99.9% confidence level. The sample size is 852

a correlation analysis between Siberian high pressure, which is closely related to East Asian monsoon intensity, and the variability of Arctic sea ice. It is found that there is a clear opposite phase between them with a correlation coefficient of − 0.64, which exceeds the confidence test level of 99.9%. This result indicates that the influence of Arctic sea ice variation on the East Asian monsoon in summer and autumn is objective, and the strength of the East Asian monsoon can have an important influence on the temperature in China (He et al., 2007; Huang et al., 2007).

The impact of Arctic sea ice on Chinese crop yield is achieved mainly through a dynamic process. When the Arctic sea ice decreases (increases) in the previous summer and autumn, the polar air pressure decreases (increases), the air pressure gradient in the middle and high latitudes increases (decreases), the AO appears in a positive (negative) phase, the Siberian high pressure strengthens (weakens) in the previous autumn, and the air temperature in the East Asian and Chinese regions appears to increase (decrease) in spring and summer as well autumn. This ultimately leads to an increase (decrease) in crop yield in China.

3.5 Forecast of China's major grain yields

The above analysis explored the process and facts of the influence of Arctic sea ice on Chinese crop yield, and the primary purpose of the study was to predict China's crop yield change and provide a reference for the national economic construction policy.

We selected the quadratic regression model for crop yield prediction, used the stepwise multiple nonlinear regression method to analyze and screen the factors associated with the Arctic sea ice changes, and obtained four factors that passed the reliability test to develop the prediction model of China's crop yield with determination coefficient is 0.99.

$$
\begin{aligned}
W = & -2874.883 - 612.235 \times X - 2887.023 \times Y + 2475.473 \times Z + 1792.015 \times K + 319.124 \times X^2 \\
& +219.671 \times Y^2 - 173.061 \times Z^2 - 11.8 \times K^2 + 543.246 \times X \times \mathrm{Z} - 526.321 \times X \times Y - 947.600 \times Z \times Y \\
& +68.748 \times K \times X - 23.878 \times K \times Y + 117.332 \times K \times Z
\end{aligned}
$$

where W, X, Y, Z and K denote China's major crop yield, ASIC in the last summer and fall, Siberian high-pressure index in the last fall, Arctic temperature in the last fall and CO_2 in the last fall and winter, respectively.

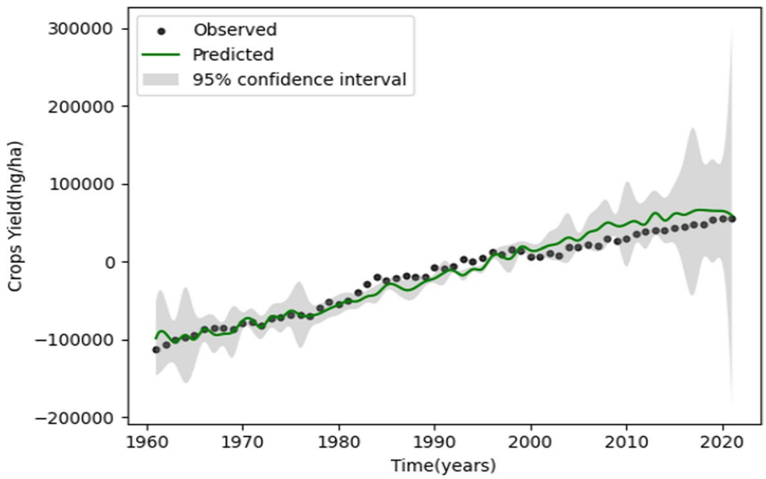

Fig. 9 Predicted (green curve) and observed (black dots) Chinese crop yield from 1960 to 2021. The gray shaded area indicates the 95% confidence interval

Figure 9 shows the variation of the observed annual average of China's crop yield with the regressed predicted yield, and the gray shading represents the 95% confidence interval. From the figure, it can be seen that the prediction model established by using nonlinear multiple regression has a great fit. Accordingly, the forecast for China's crop yield in 2022 is 59,087 (hg/ha), which continues to show an increasing trend in 2022, with an increase of 11.4% compared to last year.

4 Conclusion

In this paper, we analyze the impact of rapid Arctic sea ice decline on China's crop yield in the context of global warming and investigate the possible mechanism of their influence.

1. The analysis shows that there is a significant nonlinear positive correlation between Arctic sea ice change and Chinese crop yield. That is, when the Arctic sea ice is more in the previous summer–autumn, Chinese crop yield will show an increasing trend, and vice versa.
2. The effect of Arctic sea ice on Chinese crop yield is an indirect process, while the main factor that really affects China's crop yield directly is the local air temperature change. When the air temperature in China is high, the yield will show an increasing trend, and vice versa.
3. The air temperature variation in China is mainly influenced by the anomalous changes in Arctic sea ice. The process of Arctic sea ice influence on Chinese air temperature is mainly through a dynamic process. During the process, the decrease (increase) of Arctic sea ice in the previous summer–autumn will affect the decrease (increase) in the Arctic air pressure field in the previous autumn and winter, the increase (decrease) in the air pressure gradient in middle and high latitudes, the positive (negative) phase of AO, the enhancement (weakening) of Siberian high pressure in the previous autumn, and then

leads to the higher (lower) of China's air temperature in spring and summer as well autumn.

4. However, there are still some unresolved issues in this paper. The crop yield in China used in this paper involves not only the influence of global warming, the rapid decrease of Arctic sea ice and the continued increase of CO_2, but also factors such as the advancement of agricultural science management technology and artificial field management. Therefore, the Chinese crop yield studied in this paper is affected by both climate change and anthropogenic factors, and although previous authors have tried to use some methods to remove the bias caused by these non-climatic factors, it is still unclear how to effectively and accurately distinguish the effects of climatic and non-climatic factors on crop yield (Epule et al., 2018; Hill et al., 1980). Thus, how to separate the effects of natural and anthropogenic influences on crop yield under global warming is a key research issue in the future.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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