Assessment of Seasonal Variability of Extreme Temperature In Mainland China Under Climate Change

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Abstract

Grain yield may be affected in the future by climate change. Some studies have suggested that variations in the seasonal cycle of temperature and season onset could affect the efficiency in the use of radiation by plants, which would then affect yield. However, the study of the temporal variation in extreme climatic variables is not sufficient in China. Therefore, this article evaluates the distribution of extreme temperature seasonality trends in mainland China, describes the trends in the seasonal cycle, and detects changes in extreme temperature characterized by the number of hot days (HD), and frost days (FD) and the frequency of warm days (Tx90p), cold days (Tx10p), warm nights (Tn90p) and cold nights (Tn10p). All data are from the EAR5 reanalysis for the 1979-2020 periods.

The results show a statistically significant positive trend in the annual average amplitudes (A0) of extreme temperatures. The change in Txmax was the smallest, but it also accounted for 84.5% of the total area. The annual amplitude (A1) and phase (F1) experienced less variation than A0 for extreme temperatures in mainland China. A1 of the maximum temperature decreased significantly on the Tibetan Plateau and increased significantly in the Tianshan Mountains and Jungar Basin (mainly Taxman). F1 of the maximum temperature exhibit a negative trend in approximately 30% of mainland China, and the trend appeared in some regions except in the Northeast and Southwest. Although A1 of the minimum temperature was not as large as that of the maximum temperature, its distribution was very characteristic and it was almost bounded by the 400 mm isohyet, increasing in the Northwest and decreasing in the Southeast. In terms of the number of days, there was an increase in HD, Tx90p, and Tn90p, as well as a decrease in FD, Tx10p, and Tn10p. This number of days also indicates that temperature has increased over mainland China in the past 42 years.

Introduction

Climate change characterized by global warming has become one of the most important environmental problems in the world. Agriculture is one of the most directly affected by global climate change, especially crop production and food security (Guo 2015). China is the largest food-producing country in the world. Since 2003, the grain output has increased continuously. By 2020, the sown area of grain has reached $1.17 \text{ million} \times 10^8 \text{ hm}^2$ and a total yield of 6.69×10^8 (National Bureau of Statistics of China 2020). Chinese food production plays an important role in its own country and even food security in the world. China is located in eastern Eurasia, mostly at middle and high latitudes (Fig. 1). This is a sensitive and significant area for global climate change. Climate change is likely to have a significant impact on global food production, and Chinese food production is also faced with the uncertainty caused by climate change and the risk of yield reduction caused by extreme climate (Lobell et al. 2011; Lv et al. 2018; Anderson et al. 2019; Khalili et al. 2021). In the past half-century, the yield of most major crops in the world has increased significantly, mainly due to irrigation, chemical input and the extensive use of modern crop varieties (Lobell et al. 2012). However, an increasing number of studies have shown that there are two significant differences between the positive and negative effects of climate warming on

crop growth and yield (Das et al. 2020; Zhao et al. 2017; Liu et al. 2020; Liu et al. 2021; Zhang et al. 2021), and the results depend on the study areas, crops and methods.

In the past 100 years, the total amount and trend of temperature increase in China have been higher than the global average. In the last 50 years, the rise of surface temperature in China has accelerated, and climate warming is very obvious (Ding et al. 2016). From 1961 to 2018, the start date of the average growing season in China advanced, the end date was delayed, the length was extended, and the advance of the start date had a greater impact on the length extension. In addition, the advance of the start date and the increase in the length of the average growing season in China are mainly due to warming in spring (Wu et al. 2021). The extreme temperatures also show an increasing trend. During 1961–2014, the temperatures of the hottest day and coldest night in China showed a rapid upward trend, which were $0.17^{\circ}\text{C}\cdot 10\text{a}^{-1}$ and $0.52^{\circ}\text{C}\cdot 10\text{a}^{-1}$, respectively (Chen et al. 2021). From 1961 to 2018, cold days (Tx10p) and cold nights (Tn10p) in China had a decreasing trend, and the decreasing trend of Tn10p was significantly greater than that of Tx10p. Warm days (Tx90) and Warm nights (Tn90) had an increasing trend, and the increasing trend of Tn90p was significantly greater than that of Tx90p (Kong 2020). Extreme high temperatures and low temperatures can damage crop tissues and organs, delay crop growth and development or hinder flowering and fruiting, resulting in lower yields (Wei et al. 2015). An increase in extremely low temperature has a greater impact on crop yield than vegetative growth because it can accelerate crop aging and reduce grain-filling capacity (Hatfield et al. 2015).

Climate change not only affects temperature but also affects the temporal dynamics of temperature. Long-term global warming has changed the distribution of temperature changes, and extremely high temperatures have become more common in some places. The same is true for agricultural regions, where the probability of crop exposure to extremely high temperatures increases at the critical stage of reproductive growth (Gourdji et al. 2013). According to the latest studies, the contribution rate of climate warming to the yield of spring maize in Northeast China from 1981 to 2009 was 29.7%, and high temperatures above 30°C caused a 14.1% yield reduction. The increase in high temperature during the vegetative period was the main reason for the yield reduction (Zhang et al. 2021). Many studies have also focused on the impact of temperature changes in different periods on crop yield. Some scholars have collected relevant literature worldwide and used meta-analysis to conclude that $0 \sim 5^{\circ}\text{C}$ warming during the reproductive period had significant negative effects on wheat yield and its components. The decline in wheat yield is different in different climatic regions, and the negative effect of warming at night is greater than that during the daytime (Gao et al. 2019). As far as China is concerned, wheat yield increases significantly in the monsoon region but decreases significantly in the temperate continental climate region. The winter wheat yield has increased significantly with the increase in night temperature in the monsoon region (Gao et al. 2018). Another study indicated that warming up to $+3^{\circ}\text{C}$ has increased winter yield by 5.8% per $^{\circ}\text{C}$ (change rate of yield/average of yield) while reducing spring wheat yield by 16.1% per $^{\circ}\text{C}$ (He et al. 2020).

Temperature, precipitation, and plant phenology usually have seasonal cycles. With the growth of global climate studies, monitoring these seasonal trends as a means to detect the response of the Earth system

to global change has aroused great interest (Sparks et al. 2002; Kucharik et al. 2006; Eastman et al. 2013). Previous studies regarding the impact of climate warming on crop yield have more or less been related to the temporal dynamics of temperature. Most existing studies have used long-series data to analyze annual and seasonal changes or the length of the growing season, but analysis of the seasonal trend of temperature is not sufficient, especially the analysis of extreme temperature. Climate warming promotes increases in extremely high temperature indices and decreases in extremely low temperature indices, which affects crop yield. The purpose of this paper is to select several extreme temperature indices from the ETCCDI (Expert Team on Climate Change Detection and Indices), which are related to grain production. We analyze the spatial pattern and change in extreme temperature seasonal trends in mainland China over the last 42 years and detect the changes in extreme temperature events. These results are expected to increase the understanding of seasonal variations in extreme temperatures. This study provides help for studying the long-term impact trend of climate change on food production.

Data And Methodology

2.1 Data

In recent years, with the development of automatic observation technology, the number of meteorological observation stations in China has increased greatly, which improves the spatial density and frequency of observations and partially meets the needs of land-atmosphere processes and weather climate analysis. However, at the beginning of the layout, automatic observation stations were mostly placed in sections with stable communication, convenient maintenance and clear purpose, which have high relevance, but cannot provide uniform distribution and long-time series; therefore, it is difficult to meet the needs of long-term climate trend analysis at present. Reanalysis data are a set of gridded and long-series meteorological datasets based on data assimilation technology that integrate multisource observation data and numerical simulation results. This could compensate for the uneven spatial and temporal distribution of in-situ observations. At present, the main reanalysis datasets include a series of products (ERA5, ERA15, ERA40, and ERA-Interim) from the European Centre for Medium Term Weather Forecasts (ECMWF), NCEP/NCAR reanalysis I (R1) jointly developed by National Centers for Environmental Prediction (NCEP) and National Center of Atmospheric Research (NCAR), NCEP/DOE reanalysis II (R2) jointly developed by the Department of Energy (DOE), Japanese 25 year reanalysis (JRA-25) and 55 year reanalysis (JRA-55), NASA's Modern-Era Retrospective analysis for Research and Applications (merra and merra-2), etc. In May 2021, the China Meteorological Administration (CMA) released China's first-generation global/land surface reanalysis product (CRA). The product reproduces the global three-dimensional atmospheric conditions from the ground to a 55 km height since 1979, with a temporal resolution of 6 hours and a spatial resolution of 30 km. The quality of the product is generally equivalent to that of international third-generation global reanalysis products.

Although the ECMWF has recently formed the global ERA5 dataset since 1950, it is a preliminary version from 1950 to 1978, which is different in quality in some parts from that after 1979. There are some evaluation and application studies on the specific elements of the dataset at home and abroad, which

show that the quality of the dataset is significantly improved compared with the previous version (Zhao et al. 2019; Hu et al. 2019; Wang et al. 2020). Therefore, the hourly 2 m temperature data from EAR5 during 1979–2020 are used to form daily and monthly extreme temperatures, annual frost days (FD) and hot days (HD) in mainland China. The ground spatial resolution of the reanalysis data is further improved to $0.25^{\circ} \times 0.25^{\circ}$.

2.2 Methodology

2.2.1 Seasonal trend analysis of extreme temperature

The seasonal trends of monthly maximum temperature (Txmax), monthly mean maximum temperature (Txmean), monthly minimum temperature (Tnmin) and monthly mean minimum temperature (Tnmean) are examined by seasonal trend analysis (STA) in mainland China (Eastman et al. 2009). Seasonal trend analysis was initially applied to the trend analysis of image time series, and some scholars have used the methodology to analyze the minimum temperature over the La Plata River Basin in South America (Cogliati et al. 2021). Temperature and other meteorological elements are affected by solar radiation, atmospheric circulation and other factors, and their values change over time, which can be regarded as the superposition of many harmonics. The time series of any meteorological element is limited, and the maximum number of harmonics can be decomposed into half of the length of the series. Although a long-term series of meteorological elements contains a variety of time scale changes, the annual cycle is the most important; therefore, the first two harmonics can be used to simulate the original series.

First, harmonic analysis of the temperature series is carried out, including five characteristic parameters for annual and semi-annual periodicity, namely, annual average amplitude (A0), annual amplitude (A1), annual phase (F1), semi-annual amplitude (A2), and semi-annual phase (F2). Here, A0 is the annual average temperature, A1 is the annual temperature range, F1 is the starting position of the sine wave, and A2 and F2 are not clear, which can be regarded as the shape factor of the sine curve. Second, the Theil-Sen median slopes of the five parameters are estimated. This slope is then used to characterize the trend. The significance of the statistics is evaluated using the nonparametric Mann-Kendall test. Theil-Sen median slope estimation is a robust nonparametric statistical method that is insensitive to outliers and is very effective against reflecting the trend of time series data (Sen 1968; Eastman et al. 2009). Finally, the trend of these parameters can be visualized. Since there are as many as 3^5 combinations of these parameters, it is impossible to summarize all five seasonal curve shape parameters in a single image. It is generally found that the three amplitude images contain the largest amount of information and that rendering trends in A0, A1 and A2 provide an effective composition. A companion phase trend is created by rendering trends in A0, F1 and F2. According to the classes of combination, the region of interest can be selected to draw the fitting curve of the beginning and ending years of climate elements, and the seasonal trend and change of elements can be better understood by combining with the image (Neeti et al. 2011; Eastman et al. 2013).

2.2.2 Number of extreme temperature

We use five extreme temperature indices defined by the ETCCDI and HD that characterize extreme temperature. FD is defined as the annual number of days when the daily minimum temperature is less than 0°C. HD is days when the daily maximum temperature is greater than or equal to 35°C. Tn10p and Tn90p are the percentages of days in the year when the daily minimum temperature is less than 10% and is greater than 90% of the daily average minimum temperature in the standard climate period, respectively. Tx10p and Tx90p are the percentages of days in the year when the daily maximum temperature is less than 10% and is greater than 90% of the daily average maximum temperature in the standard climate period, respectively. The 90th and 10th percentiles of daily maximum/minimum temperature are calculated for a 5-day window centered on each calendar day in the base 1991–2020 period. In the last part of the paper, we evaluate the spatial distribution of the trend in temperature indices and examine the temporal evolution of the regional averages of these indices.

Results And Discussion

3.1 Seasonal trends in temperature

3.3.1 Maximum temperature

Figure 2 shows the spatial distribution of statistically significant trends in the annual average amplitude (A0), amplitudes of the annual (A1) and semi-annual cycles (A2), and phases of the annual (F1) and semi-annual cycles (F2) for monthly maximum temperature (Txmax) and monthly average maximum temperature (Txmean). Complimentarily, a summary of areas with significant trends is presented in Fig. 3.

The amplitude variation in the maximum temperature was mainly positive, and the phase variation was negative over mainland China, as shown in Fig. 2. In 1979–2020, the maximum temperatures in most parts of mainland China had a significant increase, and there was no significant decrease. The A0 of Txmax and Txmean increased significantly in 84.5% and 93.2% of areas, respectively. The regions without significant change mainly occurred on the Tibetan Plateau and South China (Fig. 2a, Fig. 2b, and Fig. 3). Studies have revealed that the South is one of the regions with the weakest warming trend in China, and the warming trend on the Tibetan Plateau ranks first among the eight major regions in China (Editing Commission of the Third National Report on Climate Change of China, 2015). In addition, the daily maximum temperature of the Tibetan Plateau from 1961 to 2015 had a warming trend (Jin et al. 2020). The areas where Txmax and Txmean significantly changed in A1 accounted for 10.0% and 9.3% of the total area of mainland China, respectively. Among them, Txmax decreased significantly, mainly on the Tibetan Plateau and Tarim Basin. The area where Txmean decreased significantly was slightly smaller than the area where it increased significantly. They appeared on the southeastern Tibetan Plateau, Tianshan Mountains and Junggar Basin (Fig. 2c, Fig. 2d, and Fig. 3). This indicates that the annual range of maximum temperature has not changed significantly in most areas over mainland China, while the annual range of maximum temperature in some areas on the Tibetan Plateau had been smaller, and that in the Tianshan and Junggar Basins had become larger. Since the amplitude of the nonzero semi-annual is not easy to interpret, it may be related to the difference in the semi-annual period or annual curve shape

in the seasonal curve (Cogliati et al. 2021). Therefore, this paper only provides the results without analysis. Figure 2e and Fig. 2f show that A2 of the maximum temperatures was approximately 1/3, showing a significant positive trend and mainly distributed in the northwestern region and Yangtze River Basin.

F1 of the maximum temperature in mainland China, approximately 30% of the area, had a significant negative trend. Among these areas, Txmax mainly occurred in northwestern China and north of the Yangtze River, while Txmean had a pattern of 'shrinking in the north and expanding in the south', the area with a significant decrease in North China decreased, and the area with a significant decrease to the south of the Yangtze River increased (Fig. 2g and Fig. 2h). F1 reflects the time when the sine waves reached a peak, which indicates that the time when the maximum temperature appeared in the above areas in the last 42 years was delayed. Some people think that the phase change was related to a variety of mechanisms, but the influence of the change in thermal mass was greater. Thermal mass on land is largely modulated by soil moisture. If soil moisture decreases, it will produce a positive phase shift (Stine et al. 2009). Because of the lack of long-term and spatial high-resolution soil moisture datasets, it is very difficult to find conclusions supporting the above soil moisture and temperature changes from the existing studies on soil moisture changes in mainland China. The significant trend of F2 was also dominated by a negative trend, with 28.3% of Txmax decreasing significantly, mainly in the Yangtze River Basin and North China. The area where Txmean decreased significantly was approximately 1/3 of Txmax (Fig. 2i and Fig. 2j).

The above results show that the maximum temperature had a significant positive trend in mainland China. What was the spatial pattern of the trend rate? Was the change trend based on monthly temperature consistent with the annual mean temperature?

Figure 4 shows the trends in Txmax and Txmean in the 1979–2020 period (Fig. 4a and Fig. 4b) together with the trends in A0 (Fig. 4b and Fig. 4d). We can see that Txmax and Txmean in mainland China had a positive trend, and the spatial distribution and magnitudes of the trend were very consistent with their A0. They had a significant linear relationship with a coefficient of determination of 0.92. This indicates that A0 from the seasonal trend analysis method, as a representative index of annual average temperature, is also suitable for the analysis of interannual temperature. From the perspective of spatial distribution, both Txmax and Txmean had a strong warming trend on the northeastern edge of the Tibetan Plateau, eastern coast, and Inner Mongolian Plateau. In addition, combined with Fig. 2 and Fig. 4, the trend rates of the regions where the maximum temperature change was not significant were also small.

The five parameters of seasonal trends together represent the temporal dynamics of climate factors, up to 243 combinations. Were there one or several combinations with certain advantages in mainland China? What was their spatial distribution? Therefore, this paper selects the first three significant combinations from five parameters to examine the main classes and spatial distribution of the seasonal trend of each temperature element.

Figure 5 shows the first three classes of significant changes in T_{xmax} and T_{xmean} , which were characterized by a significant increase dominated by A0. The seasonal trend of T_{xmax} was very distinct in mainland China, and only 9.6% of the areas did not change significantly. There were 63 significant change combinations, and the first three accounted for 46.9% of the total area. A total of 28.7% (+ 0000, red) had a significant increase in A0 and no significant increase in other parameters, mainly distributed in the northeastern and southeastern coastal areas and the Tibetan Plateau, indicating that the extreme maximum temperature in these regions increased synchronously with an insignificant temperature range, and the occurrence time of the maximum value did not change significantly. The second combination accounted for 60%, with A0 increasing significantly, while F1 and F1 decreased significantly (+ 00–, green), which was mainly distributed in the eastern Northwest China, northern Huang-Huai, and Jiang-Huai regions, indicating that the extreme maximum temperature in these regions generally increased and that the time was delayed. Both A1 and A2 also increased by 9.1% (+ 0 + 00, blue) and were mainly distributed in Northwest China and the northern margin of the Tibetan Plateau (Fig. 5a).

There were 51 combinations with significant seasonal variations in T_{xmena} in mainland China, accounting for 96.3%. The first three classes were when A0 increased significantly (+ 0000), A0 and A2 increased significantly (+ 0 + 00), A0 and A2 increased significantly, and F1 decreased significantly (+ 0+0), accounting for 34.8%, 16.2%, and 13.0% of the total area of mainland China, respectively. The first class was distributed mainly in Northeast China, North China, the Tibetan Plateau, and the southeastern coast. The second was mainly in the Northeast and Northwest, and the third appeared in the middle and lower reaches of the Yangtze River and Northwest (Fig. 5b). It can be concluded that in some regions of Huang-Huai and Jiang-Huai, the maximum temperature not only had a significant upward trend but also the time at which its maximum value appeared was significantly delayed. These two places are one of the main grain-producing regions in China, which provides some ideas for follow-up studies on the effect of temperature increases on grain yield.

A grid is randomly selected from the first three types of T_{xmax} and T_{xmena} , and the monthly dynamics of the start year (1979, black curve) and end year (2020, red curve) are fitted (Fig. 6). We can see that the shapes of the curves are different due to different parameter combinations. Even if the same class was different due to locations and elements, the seasonal trend of the same class of curves, regardless of their shapes, was consistent. For example, when A0 increased significantly (+ 0000), the overall value in 2020 was higher than that in 1979. When F1 decreased significantly, the peak time was obviously delayed (+ 00–, + 0+0). However, the curve of a significant increase only in A0 of T_{xmax} seems to have been significantly delayed in 2020, but the statistical test is not significant, which should be related to the large difference in the time of the maximum at this grid.

3.3.2 Minimum temperature

Similar to the maximum temperature, the minimum temperature also had a significant increase in mainland China. The A0 of monthly minimum temperature (T_{nmin}) and monthly average minimum temperature (T_{nmean}) increased significantly in 92.4% and 97.9% of areas, respectively. From this point of view, the warming of the minimum temperature was larger than that of the maximum temperature,

which is consistent with existing studies (Wang et al. 2018; Wu et al. 2017), but the time variation of its minimum value was slightly smaller than that of the maximum temperature (Fig. 7g and Fig. 7h). The regions where A0 of the minimum temperature did not change significantly were scattered on the Tibetan Plateau, Northwest China, and Northeast China (Fig. 7a and Fig. 7b). In contrast, the minimum temperature in the mid-lower reaches of the Yellow River, Yangtze River Basin, Jiang-Nan, South, and eastern Southwest China showed a positive trend in the last 42 years. The above regions are major agricultural areas in China. The regions where A1 of Tnmin and Tnmean increased and decreased significantly were bounded by the 400 mm isohyet in mainland China, i.e., the temperate continental and plateau mountain climatic areas mainly increased, while the monsoon climatic areas mainly decreased (Fig. 4c and Fig. 4d). Comparing the spatial distribution of the parameters of maximum temperature and minimum temperature, we can find that A0, A1, A2, and F1 of maximum temperature; A0, A1, F1, and F2 of minimum temperature; and their trend of Txmax/Tnmin and Txmean/Tnmean had similar spatial patterns. However, A2 of minimum temperature was an exception. Tnmin showed no change in most regions, while Tnmean showed a significant increasing trend in northern China (Fig. 7e and Fig. 7f).

F1 of Tnmin had a significant change in 8.6% of the area, and the area with a significant increase was slightly smaller than that with a significant decrease (Fig. 7g). F1 of Tnmin decreased significantly in 14.4% of the area and increased significantly in 3.1% of the area (Fig. 7h). The area where F2 changed significantly was further reduced, accounting for 3.2% and 3.7%, respectively (Fig. 7i and Fig. 7j).

In the last 42 years, the spatial distribution and magnitude of the trend of minimum temperature were also similar to the trend of A0, and their linear regression determination coefficients were 0.96 and 0.94, respectively. The warming trends of Tnmin and Tnmean were generally higher in the north and lower in the south. The warming trend rate for most parts of the North was $0.04 \sim 0.08^{\circ}\text{C}\cdot\text{a}^{-1}$, and that for the South was not more than $0.04^{\circ}\text{C}\cdot\text{a}^{-1}$. The spatial patterns of the warming trends of Tnmin and Tnmean were also similar, and the warming trend rate of the former was higher than that of the latter (Fig. 8).

The seasonal trend of Tnmin was very distinct in mainland China, and all were mainly characterized by significant changes in amplitude, which was somewhat different from the maximum temperature. A total of 94.7% of the areas had significant changes, including 57 combinations. The first three classes of significant change accounted for 78.1% of mainland China, and the first class (+ 0000) was the most distinct, accounting for 67.6% of the total area. The A0 and A1 classes increased (+ + 000) and the A0 increase and A1 decrease (+ - 000) accounted for 5.3% and 5.1%, respectively, and they appeared in the western and central regions, respectively (Fig. 9a and Fig. 10).

The first three classes with significant seasonal trends in Tnmean were also dominated by amplitude, and all had increased significantly. A0 increased significantly (+ 0000), and both A0 and A2 increased significantly (+ 0 + 00). The three amplitudes all increased significantly (++ + 00), accounting for 52.2%, 12.6% and 5.8% of mainland China, respectively, and the latter two mainly appeared in northwestern China (Fig. 9b and Fig. 10).

From the three fitting curves, we can see the seasonal trends of T_{nmin} and T_{nmean} . Because these three classes are amplitude combinations, the phase change was insignificant at the beginning year and the end year; that is, the time of peak appearance was no different (Fig. 10).

3.2 Change of extreme temperature days

3.2.1 Hot days, Cold days and Warm days

During 1979–2020, HD increased significantly in the eastern and northwestern regions (22.7%), with trend rates of $0.2 \sim 0.6 \text{ d} \cdot \text{a}^{-1}$ and $0.6 \sim 0.8 \text{ d} \cdot \text{a}^{-1}$ in some regions of the lower reaches of the Yangtze River. The area of significant decrease was small (5.3%), mainly in the northeast (Inner Mongolia and parts of Liaoning), and their trend rate was not more than $-0.2 \text{ d} \cdot \text{a}^{-1}$ (Fig. 11a and Fig. 11b). HD in most parts of the North, Northwest and Tibetan Plateau had no significant change, which is related to the fact that there were few or no temperatures higher than 35°C .

T_{x10p} decreased significantly in eastern China, eastern Northwest China, and most of the Tibetan Plateau. Most other regions had a decreasing but not significant trend. The trend rate of the significant reduction was $-0.4 \sim -0.2\% \text{ d} \cdot \text{a}^{-1}$. In western Xinjiang, there was an increasing trend and a significant increase in the Tianshan region, but the trend rate did not exceed $0.2\% \text{ d} \cdot \text{a}^{-1}$ (Fig. 11c and Fig. 11d). T_{x90p} had a significant increase in most regions, and the trend was not significant in adjacent areas of the South, Southwest and Jiang-Nan, eastern Northwest, Tibetan Plateau and most of the Tarim Basin. In terms of the spatial distribution of the increasing trend rate, most regions were less than $0.4\% \text{ d} \cdot \text{a}^{-1}$, and the increasing trend was slightly prominent in the eastern northwestern and southern southwestern regions (Fig. 11e and Fig. 11f).

The regional average of HD, T_{x10p} and T_{x90p} show that HD and T_{x90p} had an obvious increasing trend, while T_{x10p} had a decreasing trend (Fig. S1). The average HD does not seem to have been high in mainland China. This is mainly due to the vast territory of China, with large differences from east to south and from north to south. Some regions in the Northeast and Tibetan Plateau do not experience daily temperatures above 35°C , while the Southeast and Turpan Basin may have temperatures as high as 40 days, which further indicates that HDs in warm regions have increased significantly. From the regional trend rate, HDs and T_{x10p} were not as large as T_{x90p} , which was mainly related to the increase in T_{x90p} in most of mainland China.

3.2.2 Frost days, cold days and warm days

FD mainly occurs in winter, early spring and late autumn in China. HD is closely related to latitude and altitude. For example, some regions on the Tibetan Plateau have frost year round, while most regions in South China have frost-free days for approximately 350 days out of the year. During 1979–2020, the change in FD was not significant in most of the area south of the Yangtze River, and the decreasing trend north of the Yangtze River was significant. In addition to the change in FD, this distribution pattern may also have been related to a few HD in the South. In the regions where FD decreased significantly, the trend

rate was mostly $-0.2 \sim 0.8 \text{ d}\cdot\text{a}^{-1}$, and it could reach $-0.8 \sim 1.0 \text{ d}\cdot\text{a}^{-1}$ in some regions on the Loess Plateau and Tibetan Plateau (Fig. 12).

Tn10p decreased significantly in most regions, but they were not significant in the northwestern and northeastern regions. In western Inner Mongolia and the Tarim Basin, there were insignificant increasing trends. The trend rate of a significant decrease in most regions did not exceed $0.2\%\text{d}\cdot\text{a}^{-1}$ (Fig. 12c and Fig. 12d). Warm nights (Tn90p) had a significant increasing trend in most regions, but the increase was not significant only in some regions of southern Jiang-Nan and western Jiang-Han and east of Southwest China. In terms of the spatial distribution of trend rates, Tn90p had increased more significantly in western than in eastern China (Fig. 12e and Fig. 12f).

After the regional average in mainland China, both FDs and Tn10p had a decreasing trend, and Tn90p had an increasing trend. From the absolute value of the trend rate, Tn10p was smaller than Tn90p, which shows that the warmer minimum temperature increased more distinctly (Fig. S2).

The present studies on extreme temperature changes in mainland China show that although the most extreme high temperatures were increasing and extreme low temperatures were decreasing, there were certain differences between regions and magnitudes. It has been reported that days of extreme temperatures at some observatories in mainland China do not conform to a normal distribution (Qian et al. 2019; Shen et al. 2017; Zhang et al. 2020; Xing et al. 2020). Therefore, this difference may be related to the methods and data.

Conclusions

Based on the ERA5 reanalysis dataset, this paper analyzes the seasonal trends of monthly minimum temperature (Tnmin), average minimum temperature (Tnmena), monthly maximum temperature (Txmax), and average maximum temperature (Txmean) in mainland China from 1979 to 2020, as well as the change in the number of days/nights for each parameter: hot days (HD), frost days (FD), cold days (Tx10p), warm days (Tx90p), cold nights (Tn10p), and warm nights (Tn90p). Extreme temperature presented trends in the seasonal cycle and variations. We describe the trend in terms of the amplitudes and phases.

Txmax and Txmean had the same annual cycle change with a significant positive trend. The five characteristic parameters for annual and semi-annual cycles in Tmax and Txmean were similar in spatial distribution, indicating that Tmax and Txmean in most parts of mainland China had homogeneous seasonal variations. The trend in annual average amplitude (A0) was largest, and the annual amplitude (A1) was smallest. The areas with significant changes in annual phase (F1) and semi-annual phase (F2) mainly decreased, which indicates that the time of maximum temperature in these regions had a delaying trend. The area with a higher trend rate in Tmax was larger than that in Txmean, but the trend rate of both was less than $0.06^\circ\text{C}\cdot\text{a}^{-1}$ in most regions, showing a strong warming trend on the northeastern edge of the Tibetan Plateau, eastern coast and Inner Mongolian Plateau. The maximum

temperature had changed significantly to over 90% of mainland China, and the changes in A0 were dominant.

The A0 values of Tnmin and Tnmena in most of mainland China also had a significant warming trend; the trend rate was $0.02 \sim 0.08^{\circ}\text{C}\cdot\text{a}^{-1}$, which was higher in the north than in the south, and the Tibetan Plateau was especially prominent. The Tnmin warming trend was higher than that of Tnmean. The significant change area of A1 was significantly smaller than that of A0, dispersing on both sides of the 400 mm isohyet; that is, the northwestern area mainly increased, and the southeastern area mainly decreased. Different from the maximum temperature, the area where F1 with the minimum temperature changes significantly decreased, and the areas with increasing trends increased. The change in A0 in minimum temperature was also dominant, and its proportion was higher than maximum temperature, which shows that the trend in minimum temperature in mainland China was more distinct than maximum temperature.

In recent years, the number of heat waves has increased. HD has increased significantly in the eastern and northwestern regions (significantly increased areas account for 22.7% of mainland China). However, there was no significant change in those areas where HD may have occurred in South China, east of Southwest China, south of North China, and Northwest China. Tx90p had a significant increase in most regions, while Tx10p had a significant decrease on the eastern Tibetan Plateau, most of the Tibetan Plateau and eastern Northwest China. In particular, FD decreased significantly on the Tibetan Plateau. Tn10p decreased significantly in most regions but did not change significantly in the Northwest and Northeast. Tn90p increased significantly in most regions.

Declarations

Funding statement

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Author contribution

Junfang ZHao and Jianping Li contributed to the study conception and design. Material preparation, data collection and analysis were performed by Weixiong Yan and Yunxia Wang. The first draft of the manuscript was written by Weixiong Yan, and all authors commented on subsequent versions of the manuscript. All authors read and approved the final manuscript.

Data availability ERA5 daily temperature data used in this paper are available at ECMWF website (<https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5>).

Code availability Not applicable.

Ethics approval Authors declare that all the accepted principles of ethical and professional conduct have been followed in this research work.

Consent to participate Not applicable.

Consent for publication Authors give the publisher the permission to publish this work. If required, we will also provide the signed consent to publish this paper

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

References

1. Guo JP (2015) Advances in impacts of climate change on agricultural production in China. *J App Meteor Sci* (In chinese) 26(1):1–11. DOI:10.11898/1001-7313.20150101
2. National Bureau of Statistics of China (2020) Statistical communiqué of the People's Republic of China on the 2020 national economic and social development. Beijing. China Statistics Press
3. Lobell DB, Schlenker W, Costa-Roberts (2011) Climate Trends and Global Crop Production since 1980. *Sci* 333(6042):616–620. DOI:10.1126/science.1204531
4. Lv ZF, Zhu Y, Liu XJ, Ye HB, Tian YC, Li FF (2018) Climate change impacts on regional rice production in China. *Clim Chang* 147:523–537. <https://DOI.org/10.1007/s10584-018-2151-0>
5. Anderson W, Seager R, Baethge WE, Cane MA, You LZ (2019) Synchronous crop failures and climate-forced production variability. *Sci Adv* 5(7), eeaw1976. DOI: 10.1126/sciadv.aaw1979
6. Khalili P, Masud B, Qian BD, Mezbahuddin S, Dyck M, Faramarzi M (2021) Non-stationary response of rain-fed spring wheat yield to future climate change in northern latitudes. *Sci Total Environ* 772:145474. <https://DOI.org/10.1016/j.scitotenv.2021.145474>
7. Lobell DB, Gourdji SM (2012) The Influence of Climate Change on Global Crop Productivity. *Plant phys* 1686–1697. DOI:10.1104/pp.112.208298
8. Das J, Poonia V, Jha S, Goyal MK (2020) Understanding the climate change impact on crop yield over Eastern Himalayan Region: ascertaining GCM and scenario uncertainty. *Theor Appl Climatol* 142:467–482. <https://DOI.org/10.1007/s00704-020-03332-y>
9. Zhao C, Liu B, Piao SL, Wang XH, Lobell DB, Huang Y, Huang MT, Yao YT, Bsaau S, Ciais P, Durand J-L, Elliott J, Ewert F, Janssens IA, Li T, Lin ED, Liu Q, Martre P, Müller C, Peng SS, Peñuelas J, Ruane AC, Wallach D, Wang T, Wu DH, Liu Z, Yan Z, Zhu ZC, Asseng S (2017) Temperature increase reduces global yields of major crops in four independent estimates. *Proc Natl Acad Sci USA* 114(35):9326. DOI:10.1073/pnas.1701762114
10. Liu Y, Li N, Zhang ZT, Huang CF, Chen X, Wang F (2020) The central trend in crop yields under climate change in China: A systematic review. *Sci Total Environ* 704:135355.

<https://DOI.org/10.1016/j.scitotenv.2019.135355>

11. Liu WH, Ye T, Shi PJ (2021) Decreasing wheat yield stability on the North China Plain: Relative contributions from climate change in mean and variability. *Int J Climatol* 41(S1):2820–2833. <https://DOI.org/10.1002/joc.6882>
12. Zhang Y, Shou W, Maucieri C, Lin F (2021) Rainfall increasing offsets the negative effects of nighttime warming on GHGs and wheat yield in North China Plain. *Sci Reports* 11:6505. <https://DOI.org/10.1038/s41598-021-86034-3>
13. Ding YH, Wang HJ (2016) Newly acquired knowledge on the scientific issues related to climate change over the recent 100 years in China. *Chin Sci Bull (in Chinese)* 61(10):1029–1041. DOI:10.1360/N972015-00638
14. Wu BL, Jiang DB, Wang XX (2021) Changes in the Growing Season Across China during 1961–2018 (in Chinese). *Chin J Atmos Sci* 45(2):424–434. DOI:10.3878/j.issn.1006-9895.2010.20110
15. Chen HP, Sun JQ (2021) Anthropogenic influence has increased climate extreme occurrence over China. *Sci Bull* 66:749–752. <https://DOI.org/10.1016/j.scib.2020.12.001>
16. Kong F (2020) The change of extreme cold and warm events in China from 1961 to 2018 and their spatial differences. *Water Resources Hydropower Engineering* 51(9): 34–44. DOI:10.13928/j.cnki.wrahe.2020.09. 004
17. Wei X, Wang P, Zhang Z, Chen Y, Song X, Shuai JB, Shi PJ, Tao FL (2015) Assessing the Impact of Climate Change on Crop Yield Based on Three-interval Temperature Theory: A Case Study of Maize in Heilongjiang Province (1960–2009). *J Nat Resour (in Chinese)* 30(3):470–479. DOI:10.11849/zrzyxb.2015.03.010
18. Hatfield JL, Prueger JH (2015) Temperature extremes: Effect on plant growth and development. *Weather Climate Extremes*. <http://dx.DOI.org/10.1016/j.wace.2015.08.001>
19. Gourdji SM, Sibley AM, Lobell DB (2013) Global crop exposure to critical high temperatures in the reproductive period: historical trends and future projections. *Environ Res Lett* 024041. DOI:10.1088/17488-9326/8/2/024041
20. Zhang Y, Zhao YX, Sun Q (2021) Increasing maize yields in Northeast China are more closely associated with changes in crop timing than with climate warming. *Environ Res Lett* 16:054052. DOI:10.1088/1748-9326/abe49
21. Gao ML, Tang LY, Wu ZX, Zhang XB, Sun ZG, Sun N, Gao YH, Zhang CY (2019) Response of wheat yield components in global climatic zones to the warming during reproductive period. *Journal of Plant Nutrition Fertilizers (in Chinese)* 25(7):1247–1256. DOI:10.11674/zwyf.18247
22. Gao ML, Zhang XB, Sun ZG, Sun N, Li SJ, Gao YH, Zhang CY (2018) Wheat yield and growing period in response to field warming in different climatic zones in China. *Scientia Agricultural Sinica* 51(2):386–400. DOI:10.3864/j.issn.0578-1752.2018.02.017
23. He D, Fang SB, Liang HY, Wang EL, Wu D (2020) Contrasting yield responses of winter and spring wheat to temperature rise in China. *Environ Res Lett* 15:124038. <https://DOI.org/10.1088/1748-9326/abc71a>

24. Sparks TH, Menzel A (2002) Observed changes in seasons: an overview. *Int J of Climatol* 22:1715–1725. <https://DOI.org/10.1002/joc.821>
25. Kucharik CJ, Barford CC, Maayar E-M, Wofsy SC, Monson RK, Baldocchi D (2006) A multiyear evaluation of a dynamic global model at three AmeriFlux forest sites: Vegetation structure, phenology, soil temperature, and CO₂ and H₂O vapor exchange. *Ecol Modell* 196(1):1–31. DOI:10.1016/j.ecolmodel.2005.11.031
26. Eastman JR, Sangermano F, Machado EA, Rogan J, Anyamba A (2013) Global Trends in seasonality of normalized difference vegetation index (NDVI), 1982–2011. *Remote Sens* 5(10):4799–4818. DOI:10.3390/rs5104799
27. Zhao B, Zhang B, Shi CX, Liu JW, Jiang LP (2019) Comparison of the Global Energy Cycle between Chinese Reanalysis Interim and ECMWF Reanalysis. *J Meteorol Res* 33(03):563–575. DOI:10.1007/s13351-019-8129-7
28. Hu GJ, Zhao L, Wu X, LI R, Wu T, Su Y, Hao J (2019) Evaluation of reanalysis air temperature products in permafrost regions on the -Tibetan Plateau. *Theor Appl Climatol* 138:1457–1470. <https://DOI.org/10.1007/s00704-019-02888-8>
29. Wang XN, Prigent C (2020) Comparisons of Diurnal Variations of Land Surface Temperatures from Numerical Weather Prediction Analyses, Infrared Satellite Estimates and In Situ Measurements. *Remote Sens* 12(3):583. DOI. 10.3390/rs12030583
30. Eastman JR, Sangermano F, Ghimire B, Ghimire H (2009) Seasonal trend analysis of image time series. *Int J Remote Sens* 30(10):2721–2726. DOI:10.1080/01431160902755338
31. Cogliati MG, Müller G, Lovino MA (2021) Seasonal trend analysis of minimum air temperature in La Plata river basin. *Theor Appl Climatol* 144:25–37. <https://DOI.org/10.1007/s00704-020-03512-w>
32. Sen PK (1968) Estimates of the Regression Coefficient Based on Kendall's Tau. *J Am Stat Assoc* 63(324):1379–1389. DOI:10.1080/01621459.1968.10480934
33. Neeti N, Eastman JR (2011) A contextual Mann-Kendall approach for the assessment of trend significance in image time series. *Trans GIS* 15(5):599–611. DOI:10.1111/j.146-9671.2011.01280.x
34. Editing Commission of the Third National Report on Climate Change of China (2015) The third national report on climate change. Science Press, Beijing
35. Jin Q, Yang JP, Chen HJ, He QS, Tang F (2020) Comprehensive analysis of temperature variations over Tibet Plateau from 1961 to 2015. *Journal of Lanzhou University: Nat Sci* 56(6):755–764. DOI:10.13885/j.issn.0455-2059.2020.06.007
36. Stine AR, Huybers P, Fung IY (2009) Change in the phase of the annual cycle of surface temperature. *Nat* 457:435–440. DOI:10.1038/naure07675
37. Wang L, Liu BH, Henderson M, Shen XJ, Yang LX (2018) Warming across decades and deciles: minimum and maximum daily temperatures in China, 1955–2014. *Int J Climatol* 38(5):2325–2332. DOI:10.1002/joc.5337

38. Wu XS, Wang ZL, Zhou XW, Lai CH, Chen XH (2017) Trends in temperature extremes over nine integrated agricultural regions in China, 1961–2011. *Theor Appl Climatol* 129:1279–1294. DOI:10.1007/s00704-016-1848-0
39. Qian C, Zhang XB, Li Z (2019) Linear trends in temperature extremes in China, with an emphasis on non-Gaussian and serially dependent characteristics. *Clim Dyn* 53:553–550. <https://DOI.org/10.1007/s00382-018-4600-x>
40. Shen XJ, Liu BH, Lu XG, Fan GH (2017) Spatial and temporal changes in daily temperature extremes in China during 1960–2011. *Theor Appl Climatol* 130:933–943. DOI:10.1007/s00704-016-1934-3
41. Zhang JY, Qian C. Linear Trends in Occurrence of High Temperature and Heat Waves in China for the 1960–2018 Period: Method and Analysis Results. *Clim Environ Res (in Chinese)* 25 (3): 225–239. DOI:10.3878/j.issn.1006-9585.2020.19134
42. Xing P, Yang RZ, Du WP, Dang B, Xuan CY, Xiong FL (2020) Spatiotemporal variation of high temperature day and heat wave in North China during 1961–2017 (in Chinese). *Scientia Geographica Sinica* 40(8):1365–1376. DOI:10.13249/j.cnki.sgs.2020.08.01

Figures

Figure 1

Map of mainland China including geographic divisions and provinces.

Figure 2

Trends of A0, A1, A2, F1, F2 of Tmax (a, c, e, g, i) and Tmean (b, d, f, h, j) in mainland China. NS denotes insignificant. -95 and +95 represent negative and positive trends, respectively, with a significant confidence level of 95%.

Figure 3

Percentage of mainland China with significant trends in the five parameters.

Figure 4

Theil-Sen trend (TS slope a, b) and linear trend for A0 of Txmax and Txmean (A0 slope c, d)

Figure 5

The three most prevalent classes of significant seasonal trends in Txmax and Txmean. Significant positive trends are marked with a "+" sign, significant negative trends with a "-" sign, and insignificant trends with a "0". From the left, the symbols indicate the trend in A0, A1, A2, F1, and F2. Black spots are randomly selected representative points of the three classes.

Figure 6

Examples of the three most prevalent classes of significant seasonal trends in Txmax and Txmean.

Figure 7

Trends of A0, A1, A2, F1, F2 of Tnmin (a, b, c, d, e) and Tnmean (f, g, h, i, j) in mainland China.

Figure 8

Theil-Sen trend (TS slope a, b) and linear trend for A0 of Tnmin and Tnmean (A0 slope c, d).

Figure 9

The three most prevalent classes of significant seasonal trends in Tnmin and Tnmean.

Figure 10

Examples of the three most prevalent classes of significant seasonal trends in Tnmin and Tnmean.

Figure 11

Number of hot days (HD, a, b), cold days (Tx10p, c, d) and warm days (Tx90p, e, f). Left for trend rate and right for significance.

Figure 12

Number of frost days (FD, a, b), cold nights (Tn10p, c, d) and warm nights (Tn90p, e, f). Left indicates trend rate and right for significance.