The Spatiotemporal Characteristics and Responses to Climate Warming of Thermophilic Crops in Chinese Oases between 1960 and 2016

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Abstract: Crop growth is an important controlling factor for vegetation ecosystem function, and is regarded as the “best indicator” of climate change response. The research on the response and adaptation to climate change has important theoretical and practical significance for crops adapt to global changes, mitigate disaster losses and promote grain income. Therefore, based on the daily average temperature data from 67 meteorological stations in Chinese oases that are within the distribution area of Thermophilic crops, this paper analyzed to determine the spatiotemporal responses of the start and end dates and growing period of crops to climate change. Using the multi-year trend line, inverse distance weighted interpolation (IDW) in the software ArcGIS, a Morlet wavelet power spectrum, correlation analysis and unary regression analysis. The results show that, in the past 57 years, the oasis Thermotropic crops in China have been characterized by advanced the start date, postponed the end date, and gradually increased the number of days that comprise the growing period. The changing trend rates recovered in this analysis for these three time slices are -1.44d/10a, 1.48d/10a, and 2.92d/10a ($\alpha \geqslant 0.001$), respectively. The extension of the growth period is the most prominent, the correlation coefficient is as high as 0.676, but each oasis is different. Data show that spatial disparity of Thermophilic crops is extremely significant. From the southwest to the northeast of Chinese oases, having the characteristics that the start date is postponed, the end date is advanced, the growing period is shortened. There are 2.4a, 3.5a and 2.5a, 3.8a dominant short cycles at the start and end dates and growing period of Thermophilic crops, respectively. It is indicated that the Thermophilic crops may be affected mainly by atmospheric circulation (2-4 years). It is significantly correlated with the average temperature of April, October and April to October, the correlation coefficients are -0.963, 0.928 and 0.957 ($\alpha \geqslant 0.001$).Thus, if the average temperature in April increases by 1℃, the start date will be advanced by 4.83 days, while if the average temperature in October increases by the same margin then the seasonal end date will be delayed by 4 days. Similarly, if the average temperature between April and October increases by 1℃, the growing period will be extended by 9.04 days. The results indicate that the variation of the growth period of Thermophilic crops in the study area is sensitive to the response of climate warming.

1. Introduction

Global warming has been a fact beyond doubt for almost a century. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change noted that global average surface temperature increased by 0.85℃ between 1880 and 2012, and it is also the case that warming trends within China are consistent with those seen across the rest of the world [1]. Studies have shown that the strong impact of climate change on ecosystems is changing the natural processes inherent in ecosystems, whether on a global or a regional scale [2]. Climate change has a great constraint on the agricultural ecosystem, the warming, drying or wetting of the climate will cause changes in the ecological environment, production layout and pattern of the agricultural ecosystem [3]. Agricultural production, as a system that is highly dependent on natural conditions, especially climatic conditions, is very sensitive to current climate change [4-5]. Crop growth period is an important controlling factor of vegetation ecosystem function and the most sensitive component to

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climate change [6-7]. The advance or delay of its growth period is regarded as one of the most powerful evidence for the response to climate change [8]. In addition, the growing period of crops can not only objectively reflect the changes of natural seasons, but also indicate the response and adaptation of crop growth and development to changes in the external environment [9]. Therefore, it is also regarded as the "best indicator" of crop response to climate change [10] and the "diagnostic fingerprint" of global environmental change [11-12]. And temperature is the most obvious unrestricted influence factor in the growth period of all ecosystems, which may have an amplification effect in some areas of middle and high latitudes [13]. The changes in the global environment caused by global warming have changed the start and end time and length of the growth period in many parts of the world. In the whole world, especially in the northern hemisphere, there is a trend of early start time and longer growth period [14]. Climate change has made the trend of end date of growth in 70% of the Northern Hemisphere obvious, and the change trend rate averages 0.18±0.38d/a [15]. The flowering date and flowering period of Iranian maize are shortened [16]. In the Butana arid region of Sudan, end date of growth was delayed and the number of growing days increased [17]. The length of the 20th century growing season in Illinois is also increasing [18]. In Europe, the spring phenology is advanced by 6d, and the autumn phenology is postponed by 4.8d, and the average annual growth period is extended by 10.8d [19]. The growth season extended by 18.5d on average, the start date of growth advanced by 7.1d and end date of growth postponed by 11.4d in Murmansk region of Russia [20]. Climate change has dramatically changed the growth period in semi-arid of Zimbabwe from 120 days in the early 1970s to 100 days in 2001 [21]. Length of Growing Season increased significantly, with an average growth period of 235 days and standard deviation of ±20 days in Uyo, Akwa Ibom State, Nigeria [22]. The sowing date of crops showed a trend of increasing with temperature. The sowing date of winter wheat in Germany was advanced by 5 days and that of winter rye by 1.3/10a [23-24]. It has an impact on maize cultivation in the agro-ecological region of western Uganda and maize growth in India [25-26]. The growth season in northern and central Europe (May-September) was strongly correlated with temperature ($r > 0.9$) [27]. There was also a high correlation between crop growth season and mean temperature in May and September in the former Soviet Union [28]. Under climate change, the climatic trend rate of the start date, end date and accumulated temperature of agricultural boundary temperature in China is -7.6-37.3, -47.1-40.9 and -250-456.4d/ 10a [29]. The growth in Tibetan Plateau was significantly advanced by 0.14d/a on the start date of growth and only slightly and not significantly delayed on the end date of growth (0.08d/a) [30]. In north and south China, the growth period was extended by 2.3 and 1.3d/10a on average, and the start date of growth was advanced by 1.7 and 0.6d/10a, respectively [31]. The multi-year average growth of crops in the central Yunnan region was 362.58 day, with an increase of 0.371 d/10a [32]. The temperature changes of time and space in each boundary of Qaidam basin showed that start date was advanced, end date was delayed , accumulated temperature and growing season was extended [33]. In Hexi Corridor, Hebei region and Tibetan Plateau area, the boundary temperature of ≥10℃ was presented that the start day was advanced, the end day was delayed, and the number of days between the start and the end day was increased, the start day of growth was advanced 0.4-1.4, 1.6 and 4-6d/10a, the end day of growth was delayed by 0.7-2.2, 1.0, 0.4-7.7d/10a, and the number of days increased by 1.6-2.5, 2.6, 2-10d/10a, respectively [34-36].

To sum up, most of the studies abroad focus on crop yield reduction, and varieties focus on a single maize or wheat [37-39]. Most of the domestic studies focus on the phenological or spatial changes in the central and eastern regions [40]. Most of the studies use data such as phenology, vegetation normalization index and surface temperature to illustrate the growth period [41]. Phenological phenomena can accurately reflect the fluctuation and variation of growing season under climate change, but most of the studies mainly focus on individual plants in certain regions [42-43], the results of observation and research are meaningful only in the living area or adjacent area of the plant. In addition, the regional phenology data collection workload is large and usually the time series is short. NDVI data space covers a wide range and has a high resolution, making it convenient for regional and even global climate change research [44]. However, the time resolution of NDVI data is low, which may cover up the true change of vegetation status [45]. Therefore based on 57 years of meteorological data, this paper use comprehensive methods to analyze the response of growing period of *Thermotropic crops* to global warming. Chinese oases are located in northwest China arid region where less than 5% of the land raises 95% of the population. It is the essence of the northwest arid region, as well as vulnerable and sensitive area of climate change. Crops are the main source of people's livelihood in the study area, among them, *Thermotropic crops* are relatively widespread, mainly cotton, corn, sorghum, rice and so on. How and to what extent crops respond to global warming has become an urgent scientific problem. Therefore, this paper takes the *Thermophilic crops* in oasis of China as the research object, reveals the change rules of *Thermophilic crops* in the research area in order to better reflect the sensitivity of crops to global change, it provides scientific basis for crops in arid areas to adapt to global changes, mitigate disaster losses and promote grain production.

2. Study Area

Chinese oases is located in the Eurasian Hinterland, between 34° 25′ -48° 10′ N and 73° 40′ -109° 08′ E, distributed alternately in high mountains and basins. The region of interest covers an area of nearly 1.9×10^5 km^2, and includes six oases in northern Xinjiang, southern Xinjiang, the Hexi Corridor, the Hetao Plain, the Qaidam Basin and Alxa [46]. Chinese oases are mainly distributed in northwestern China, they are mostly subject to a desert climate which consists of droughts and rare rainfall, mean annual rainfall in these regions tends to be less than 200mm; they are cold in the winter and hot in the summer, and experience large ranges of both annual and daily temperature. Light and heat re-sources at these oases are also very abundant: solar global radiation is more than 5.04×10^5 MJ/m^2, annual sunshine duration is greater than 2800 h, accumulated temperature≥10℃ is above 2600℃, and the frost-free period is about 140 days. The soils of these regions are also dominated by brown-to-gray-brown deserts and eolian sandy soils, while zonal vegetation is mostly characterized by desert and desert steppe (Figure1).

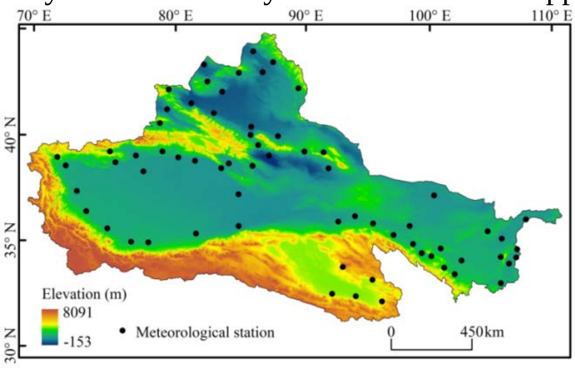


Fig.1 Distribution of Meteorological Stations of Thermophilic Cropsin Chinese Oases

3. Data and Methods

3.1 Data Source

A dataset of daily average temperatures was used in this study that encompasses the period between 1960 and 2016; these data were recorded at 67 meteorological stations that span the distributional range of crop growth in Chinese oases, all downloaded from the China Meteorological Science Data-sharing Service System (http://www.cma.gov.cn/).

3.2 Research Methods

3.2.1 The Start Date and the End Date of the Thermophilic Crops in Chinese Oases

Thermophilic crops are crops of growing season during which the daily mean temperature is more than 10 ℃ [47] and refers to crops that require a higher temperature and a higher accumulated temperature during the whole growth period, with a minimum temperature of 10 ℃ for growth and development, such as cotton, corn, sorghum, rice, and so on [48]. In this paper, the first day and the end day of stable temperature passing through the limit of 10 ℃ are used as the beginning and ending dates of the growing period of *Thermophilic crops*, the number of days between the start and end days as the number of days in the growth period. The temperature data from 1960 to 2016 are processed day by day and year by year, and the five-day moving average method is used. When the mean value of sliding is greater than or equal to 10 ℃, in the first five consecutive days of sliding mean ≥10℃, the first date ≥10℃ is used as the starting date of the growing period of *Thermophilic crops*. The last of the five consecutive days in which the average sliding average is ≥10℃, the last day ≥10℃ is used as the end date.

3.2.2 Climatic Tendency Rate

Use the accepted global climate change trend rate to indicate how fast it is changing, the trend change is represented by a single linear regression model:

$Y = a + bt_i$ (i=1,2,...,n)

b×10 is called climate tendency rate (0℃/10 a), the magnitude of the absolute value of *b* can be used to measure the extent to which the trend of evolution has increased and declined, *b*>0 indicates an upward trend in the calculation period and *b* < 0 indicates a downward trend. Then we analyze the start and end dates and growing period of the *Thermophilic crops* in the whole study area and each oasis.

3.2.3 Inverse Distance Weighted (Idw)

ArcGIS inverse distance weighted method is widely used in all deterministic interpolation methods. The IDW interpolation method can also improve the accuracy of spatial interpolation by adjusting the weight size for the regions where the distribution of stations is not very uniform. Therefore, in this paper, the start date, end date and growing period of 67 stations from 1960 to 2016 are used as parameters, and the spatial distribution characteristics are obtained by using IDW interpolation method in ArcGIS 10.2 software.

3.2.4 Morlet Wavelet Analysis

Morlet wavelet analysis method is widely used in climate, hydrology, climate change and environmental evolution in the periodic analysis at home and abroad. In this paper, the matlab software is used to input the data into the program and the application program is used to get the wavelet map of the growing period of the *Thermophilic crops*.

3.2.5 Correlational Analysis and Single Variable Linear Regression Model

They are commonly used in the study of mathematical statistics, mostly used in the fields of meteorology, hydrology and environmental evolution. Therefore, we use both methods in order to explore the intensity of the response to climate change in the start and end dates and growing period of *Thermophilic crops* in our research area. In this paper, the temperature equations of the start date, the end date of growth and the growing period and April, October and April to October respectively are established, and the correlation coefficient and confidence degree are obtained, respectively, to reflect the regional response degree of global warming, and using the above parameters to establish a univariate regression model:

$$Y_1 = a1X_1 + b1 \quad (1)$$

$$Y_2 = a2X_2 + b2 \quad (2)$$

$$Y_3 = a3X_3 + b3 \quad (3)$$

Calculating the numerical value of the growth period of *Thermophilic crops* with temperature in the study area.

4. Results

4.1 Temporal Variations in the Thermophilic Crops Growing Period

4.1.1 The Start of Growing Period

In the past 57 years, the start date of growing period of *Thermophilic crops* in Chinese oases has advanced significantly at a rate of 1.44d/10 a (α ⩾0.001) (Figure2a), while the average start date (April 26) has advanced 8.2 days over the past 57 years, the study area was the earliest in April 5, 2009 and the latest in May 7, 1982. The obvious degree of early and late advances and trends in the start date in each oasis are different (Figure3. a1-f1), among which the southern Xinjiang oasis was the earliest on April 4, followed by the Hetao oasis was April 18, the Alxa oasis was April 20, and the Hexi Oasis was April 21, the northern Xinjiang oasis was May 4, the Qaidam Basin oasis was the latest on May 28, while the most obvious advancing trend was seen in the Qaidam Basin oasis, where the change rate is -2.28d/10a, the start date of growing period of *Thermophilic crops* has advanced 13 days over the last 56 years. The most unclear trend in advancing start date was seen in the Alxa oasis that the rate of change is -1.042d/10a, the start date of growing period of *Thermophilic crops* has advanced by just 6 days over the past 56 years. It reflects that Qaidam oasis is located on the Qinghai-Tibet Plateau and is the unique characteristic of the only plateau oasis [49], the response to climate change is most obvious. This result is consistent with the conclusion that this relates to the observation that it is 'the driver and amplifier' of global climate change [50].

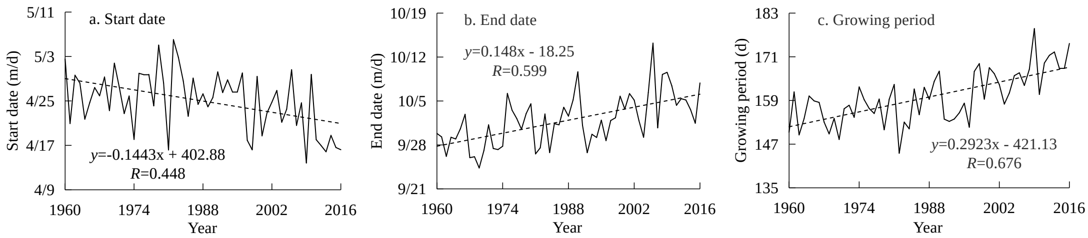
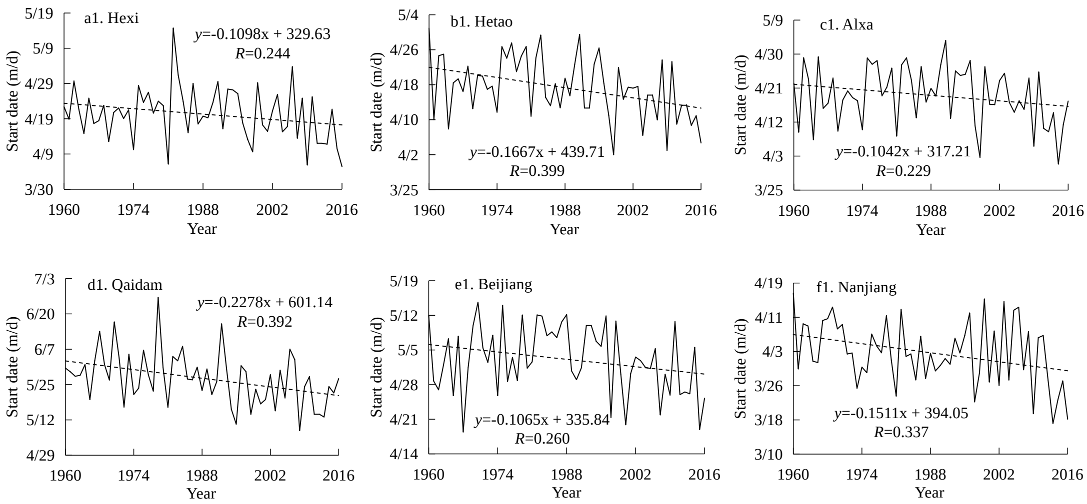


Fig.2 Variation Trend of the Onset and Upset Dates and Growing Period of Thermophilic Crops in Chinese Oases



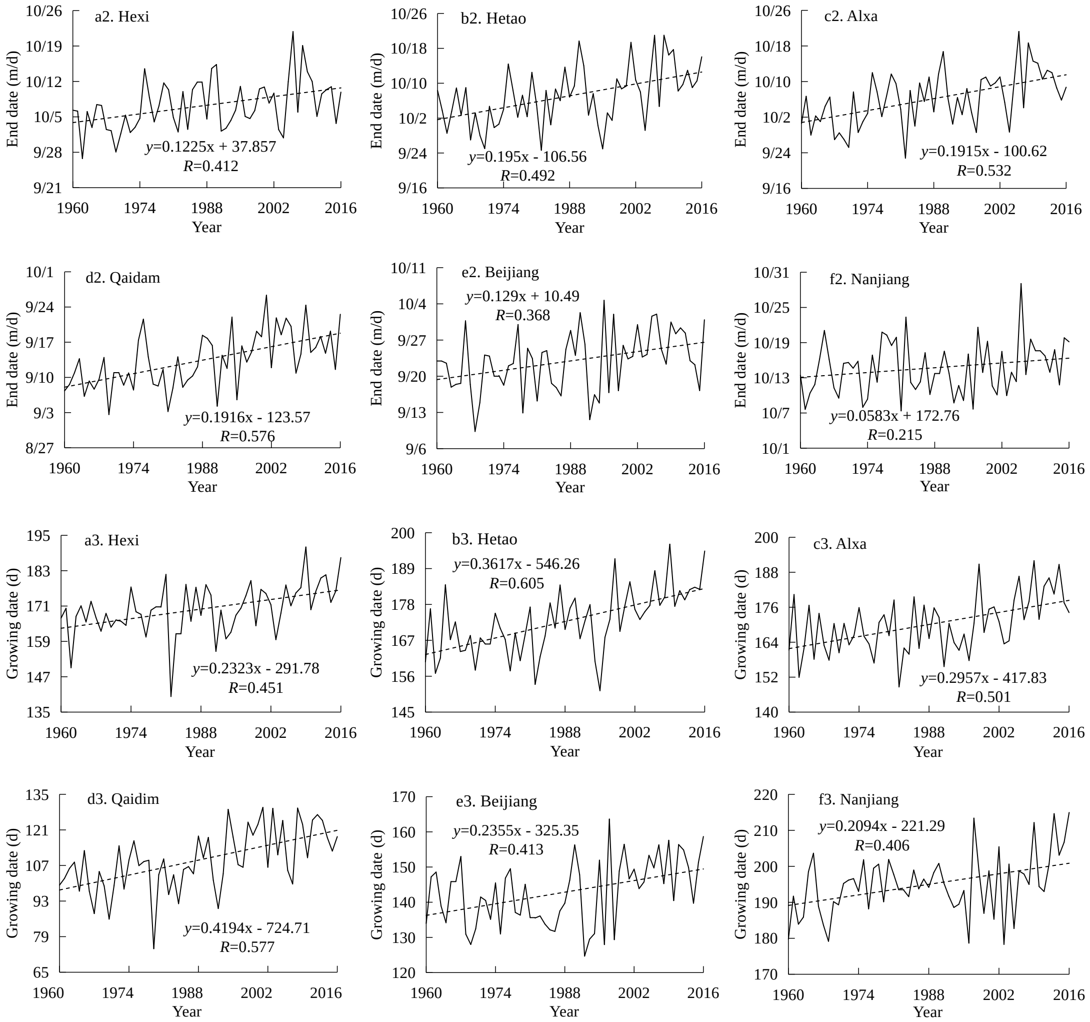


Fig.3 Variation Trend of the Onset and Upset Dates and Growing Period of Thermophilic Crops in Chinese Oases

The Inter-decadal change of the start date of *Thermophilic crops*in Chinese oases were positive anomaly in the 1960s-1990s and the start date was a marked delay in the 1970s (Table1). From the 1990s to the 2000s, however, anomaly values changed from positive to negative, and the start date of *Thermophilic crops* also showed a significant trend in advance. From the 2000s to the 2010-2016, the change of anomaly value was the most significant, reaching a maximum value of 6.1 days in the 2010-2016. these data revealed that the advance trend of start date of *Thermophilic crops* in the 2010-2016 is most obvious.

Table 1 Decadal Thermophilic Crops Growing Season Anomalies in Chinese Oases

Decade	Start date (d)	End date (d)	Growing period (d)
1960-1969	1.4	-3.6	-5.0
1970-1979	2.5	-1.3	-3.8
1980-1989	1.8	-0.7	-2.5
1990-1999	0.8	-0.2	-1.1
2000-2009	-2.2	3.7	5.9
2010-2016	-6.1	3.1	9.2

4.1.2 The End of Growing Season

In the past 57 years, the end date of *Thermophilic crops* in Chinese oases has been significantly delayed (Figure2b). The trend rate of change was 1.48 d/10a, and the average annual end date of growth period was on October 3, the average end date of *Thermophilic crops* was delayed by 8.4 days over the last 57 years. It is also different that the end date of *Thermophilic crops* of each oasis is delayed sooner or later (Figure3.a2-f2). Among them, Qaidam oasis was the earliest on September 14, followed by the northern Xinjiang oasis was September 24, the Alashan oasis was October7, the Hexi oasis and the Hetao Plain oasis both were October8, the southern Xinjiang oasis was October16at the latest. The most obvious tendency to delay of the end date was the Hetao Plain oasis, the trend rate of change is 1.95 d/10a, and it has been delayed by 11 days over the past 57 years. The most not obvious tendency to delay of the end date was the southern Xinjiang oasis, the trend rate of change is 0.463 d/10a, and it has been delayed by only 3.3 days over the past 57 years, it is mainly due to the southern Xinjiang is located in the south of Tianshan mountain and the terrain is closed, it belongs to the warm temperate climate.

The inter-decadal change of the end date of *Thermophilic crops* in Chinese oases was negative between the 1960s and the 1990s (Table1), its absolute value decreased gradually, and the end date was gradually delayed. From the 21st century, the anomaly value changed from negative to positive, which between 3.1 to 3.7, the change of anomaly value between the 1990s and 2010s was the most significant, in addition, the maximum value was 3.7 days in the 2010s, which shows that the tendency to delay of the end date of *Thermophilic crops* in the 2010s is most significant.

4.1.3 The Number of Growing Season Days

In the past 57 years, the annual growth of the *Thermophilic crops* in Chinese oases has been significantly extended (Figure2c), and the trend rate of change is 2.92d/10a, which has been extended for a total of 16.7days in 57 years. The perennial average growth rate of the *Thermophilic crops* was 160days, and the longest average growth period was 179days in 2009, the shortest was 145days in 1982.But growth period of each of the oasis is different (Figure3. a3-f3), among them, The average growth period of the northern Xinjiang oasis was 143days, southern Xinjiang oasis was 195days, Hexi oasis was 170days, Qaidam oasis was 109days, Hetao oasis was 173days, Alxa oasis was 170days, the longest growth period in the study area obviously is southern Xinjiang oasis, and the growth period trend is the least obvious, the change tendency rate is 2.094d/10a, the growth period has been extended by 12days over the past 57 years, with the same as characteristics that the southern Xinjiang oasis is located in Tarim basin, the cold air is hard to get in, the heat is easy to get together, the climate is warm temperate climate and warmer. The shortest growth period is the Qaidam oasis, and the growth period trend is themost obvious, the change tendency rate is 4.194d/a, a total of 24days was extend edover the past 57 years, this is because the Qaidam oasis is plateau oasis, having high altitude, and the most sensitive to climate warming, it is consistent with the most sensitive research conclusions on global climate change response in the Qinghai-Tibet Plateau.

The annual growth of the *Thermophilic crops* in Chinese oases has been significantly extended, the inter-decadal changes are different (Table1), the departure value both was negative in the 1960s and 1990s, and its absolute value decreased gradually, the growth period extended gradually. At the beginning of the 21st century, the departure value changed from the negative to the positive and value was gradually increased, and growth period extending was more obvious, from the 1990s to the first decade of the 21st century, the change of value was the biggest, increased the 7days, the departure value is as high as 9.2 days from 2010 to 2016 and the extended tendency of growth period of *Thermophilic crops* is most obvious.

In sum, the *Thermophilic crops* in Chinese oases has shown a trend such that the start date, end date and growth period respectively has been advanced, delayed and extended over the past 57 year. It is shown that the *Thermophilic crops* in Chinese oases is as sensitive to global warming as regional temperature.

4.2 Spatial Variations in the Thermophilic Crops Growing Period in Chinese Oases

We investigated the spatial variation characteristics of mean start and end dates values as well as growth period of the *Thermophilic crops* by using 67 meteorological stations within Chinese oases, take 57 years average and change tendency rate as parameters, drawing spatial variation figure by applying the IDW interpolation method.

The results show that the spatial variation of *Thermophilic crops* in Chinese oases is significantly different in the start and end dates, as well as the growth period (Figure 4),it has characteristics of spatial variation that the growth period has tended to shorten over time, the start date has tended to be delayed while end date has advanced from southwest to northeast over Chinese oases, and this variation is particularly evident in the Xinjiang oasis. As can be seen from the spatial changes, the start date of the *Thermophilic crops* growing period has varied between March 20th and June 11th, range difference of 83 days, the earliest growing season start date in the southern Xinjiang oasis and the latest in the Qaidam oasis. The end date of the *Thermophilic crops* growing period has varied between September 8th and October 25th, range difference of 47 days, the latest growing season end date in the southern Xinjiang oasis and the earliest in the Qaidam oasis. The growth period of *Thermophilic crops* ranged from 89-217days, with a difference of 128days, it was still the longest growing period in the southern Xinjiang oasis and the shortest in the Qaidam oasis. Obviously, the earliest start date, the latest end date, and the longest growth period of the *Thermophilic crops* were all seen in southwestern of the southern Xinjiang oasis. This is because the southern Xinjiang is located in the Tarim Basin, this terrain occlusion means that cold air is difficult to enter, and the underlying surface of this region comprises gobi desert and heat is easily gathered, so the southern Xinjiang oasis has more heat and warmer climate. Qaidam Basin oasis showed the latest start date, the earliest end date, and the shortest growth period of the *Thermophilic crops*. It is because the Qaidam basin belongs to the high altitude cold arid continental climate, and located in the Qinghai-Tibet plateau of high altitude and low temperatures.

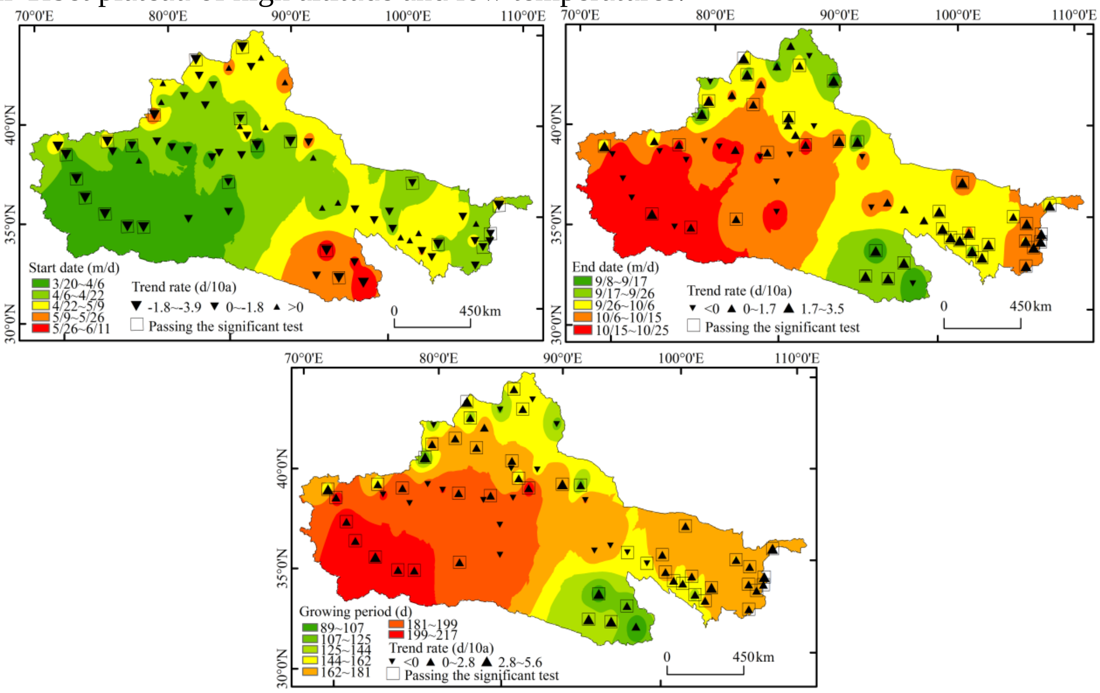


Fig.4 Spatial Distribution Trend of Onset and Upset Dates and Growing Period of Thermophilic Crops in Chinese Oases

From the trend of spatial change in the start and end dates and the growth period of the *Thermophilic crops* (Figure4), results from 96% of the stations are advanced in the start date of the *Thermophilic crops*, most sites change tendency rate is between -1.8-3.9 and only Qinghe, Hoboksar and Wenquan are delayed and not through the test of significance, from the whole oases, 33% of the sites passed the significance test of 0.05; Delaying trends of end date were seen in about 90% of stations, most sites change tendency rate is between 1.7-3.5 and only 7 sites are advanced and not through the test of significance, from the whole oases, 57% of the sites passed the significance test of 0.05; Extending trends of the growth period were seen in about 99% of stations, most sites change tendency rate is between 0-2.8 and only Wenquan is shortened and not through the test of significance, from the whole oases, 72% of the sites passed the significance test of 0.05.This indicates that the trend of prolongation is very obvious and widespread in the *Thermophilic crops* growing period in Chinese oases.

4.3 Period Analysis

We used Morlet wavelet power spectrum analysis method in order to analyze cyclical variations on the start and end dates and growth period of *Thermophilic crops* in Chinese oases. The results show that the start date have cycles of 2.4 years and 3.5 years (Figure5a, b; WPS is wavelet power spectrum), the end date have cycles of 2.5 years and 3.8 years (Figure5c, d), growth period also have cycles of 2.5 years and 3.8 years (Figure5e, f), all of them passed the 95% red noise test. While the start and end dates and growth period of *Thermophilic crops* in Chinese oases are consistent with atmospheric circulation quasi-periodicityof2-4years, it is indicated that the *Thermophilic crops* is mainly affected by atmospheric circulation.

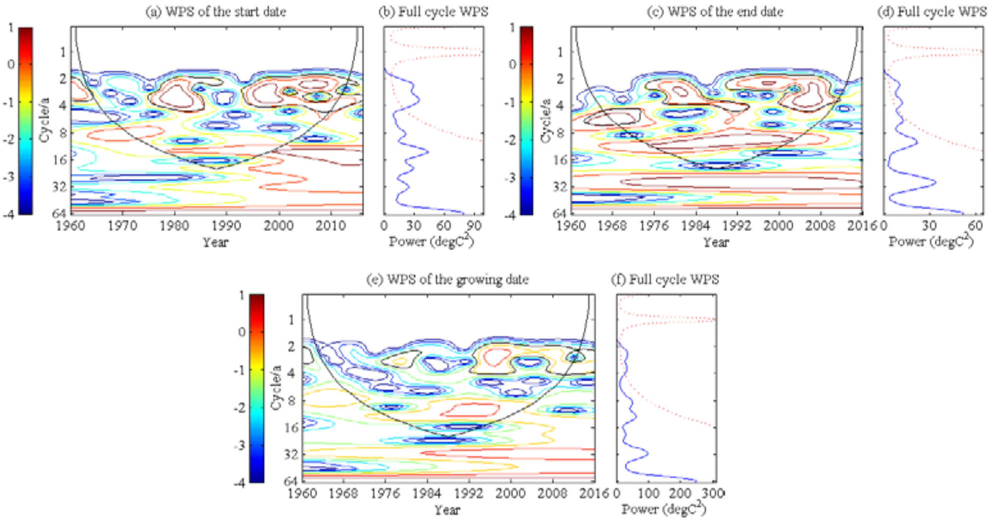


Fig.5 Wavelet Analysis of the Start Date, End Date and Growing Period of Thermophilic Crops in Chinese Oases

4.4 Relationship between Growth of Thermophilic Crops and Mean Temperature in Chinese Oases

In this paper in order to study the response relationship between the start and end dates and growth period of *Thermophilic crops* in Chinese Oases and their corresponding average temperatures, the annual average temperature and average temperature in April, October and April-October of the various stations in Chinese Oases were selected. Correlated analysis was carried on the start and end dates and growth period of *Thermophilic crops* in Chinese Oases (Figure 6).

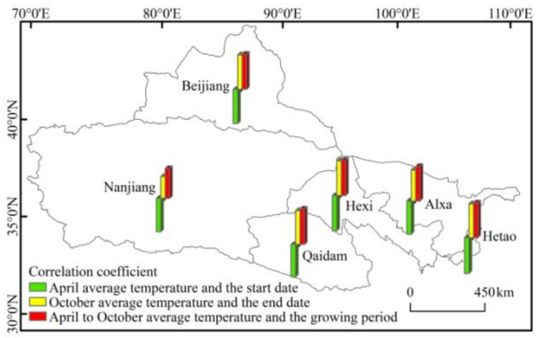


Fig.6 Correlation Analysis between the Start Date, End Date and Growth Period of Thermophilic Crops and Mean Monthly Temperatures in Chinese Oases

The results showed that there was a significant negative correlation between the start date of the *Thermophilic crops* in Chinese oases and the average temperature in April, and the correlation coefficient was -0.963 ($\alpha \geqslant 0.001$). There was also a significant negative correlation between the start date of the *Thermophilic crops*in each oasis and the average temperature in April. Among them, the Hetao Plain oasis has the highest correlation with -0.993 ($\alpha \geqslant 0.001$), and the Qaidam Basin oasis with the smallest correlation coefficient reaches -0.904 (α ⩾0.001), indicating that the higher the temperature in April, the start date of the *Thermophilic crops* will be earlier. There was a significant positive correlation between the end date of the *Thermophilic crops* in Chinese Oases and the mean temperature in October. The correlation coefficient was 0.928 (α ⩾0.001). There also was a significant positive correlation between the end date of the *Thermophilic crops* in each oasis and the mean temperature in October, among them, the Hexi oasis had the highest correlation with 0.968 (α ⩾0.001) and the southern Xinjiang oasis had the smallest correlation coefficient with 0.605 (α ⩾0.001), indicating that the higher the temperature in October, the more delayed the end date of the *Thermophilic crops*. There was a significant positive correlation between the growth period of the *Thermophilic crops* in Chinese oases and the average temperature in April-October, and the correlation coefficient was 0.957 (α ⩾0.001). There was also a significant positive correlation between the growth period of the *Thermophilic crops* in each oasis and the average temperature from April to October. The correlation coefficient is between 0.828-0.986 (α ⩾0.001). Among them, the correlation coefficient of the Qaidam Basin oasis is the highest, which indicates that the higher the average temperature from April to October, the longer the growth period of the *Thermophilic crops*.

From the correlation coefficient between the average annual temperature and the start and end dates and the growth period of the *Thermophilic crops*, the correlation between them and the annual mean temperature is extremely high, and the correlation coefficients are -0.932, 0.967, and 0.951 (α ⩾0.001), indicating that *Thermophilic crops* have an excellent response to the increased temperature on the start date and end date and growth period. And the absolute value of the correlation coefficient of the end date is greater than the absolute value of the start date, indicating that the delayed of the end date of the *Thermophilic crops* response to climate warming in Chinese oases is more significant than the start day of growth.

From the statistical analysis, the changes of *Thermophilic crops* with the temperature has a great relevance, so building the regression equation between the start and end dates and growth period of the *Thermophilic crops* and the corresponding month average temperature (the confidence coefficient is 95%, R are 0.96, 0.93 and 0.96 respectively, The F values are 822, 400 and 696).

$$Y_1 = 4.83X_1 + 165.44 \quad (4)$$

$$Y_2 = 4.00X_2 + 245.30 \quad (5)$$

$$Y_3 = 9.04X_3 + 12.85 \quad (6)$$

where Y_1, Y_2 and Y_3 denote the start and end dates and growing period of *Thermophilic crops*, and X_1 is the mean temperature of April, X_2 is the average temperature of October, X_3 is the average temperature of April to October.

The regression equation can accurately reflect the responses seen in the growing period of *Thermophilic crops* to changes in temperature. Calculations show that if the average temperature in April increases by 1℃, then the start date of *Thermophilic crops* will be advanced by 4.83 days earlier, while if the average temperature in October increases by 1℃, then the end date will be delayed by 4 days, if the average temperature between April and October increase by 1℃, then the growth period will be prolonged by 9.04 days. Obviously, these results further indicate that the response to global warming is intense in the study area.

5. Conclusion and Discussion

5.1 Conclusion

(1) This study show that the start date of the *Thermophilic crops* in Chinese oases has advanced over the last 57 years, while the end date has been postponed, and the growth period has been

gradually prolonged, at average rates of -1.44d/10a, 1.48d/10a and 2.92d/10a (α ≥0.001), respectively. In each oasis, the start and end dates and growth period of the *Thermophilic crops* in southern Xinjiang oasis were the earliest, the latest and longest. This situation is reversed in the case of the Qaidam Basin oasis. The growth period change of the Qaidam Basin oasis was most obvious, the rate of variation is 4.194d/10a. The growth period change of the southern Xinjiang oasis was least obvious, the rate of variation is 2.094d/10a. It reflects the regionality.

(2) The spatial distribution of start date, end date, and growth period of the *Thermophilic crops* exhibit significant regional differences. This paper generally show that start date have been delayed, end date have advanced and the growth period have tended to shorten over time, while along a transect from southwest-to-northeast over Chinese oases. These patterns of variation are most obvious within the southern Xinjiang oasis.

(3) The wavelet analysis show that the start and end dates and the growth period of the *Thermophilic crops* all existed 2.4 years and 3.5 years advantage short periods. This periodicity is consistent with the quasi-periodicity of atmospheric circulation 2~4 years. This shows that it is mainly affected by atmospheric circulation.

(4) Data show that the start date, the end date, and the growth period of the *Thermophilic crops* were all significantly correlated with the average temperatures in April, October, and between April and October, with correlation coefficients of -0.963, 0.928, and 0.957 (α ≥0.001), respectively. Thus, a 1℃ increase in April, October, and between April and October average temperature will cause the start date to occur about 4.83 days earlier, the end date to occur about 4 days delay and will cause the growth period to occur about 9.04 days extended of the *Thermophilic crops*. This indicates that the *Thermophilic crops* of study area is sensitive to temperature.

5.2 Discussion

(1) The advanced start date, postponed end date and the number of days that comprise the growing season have gradually increased of *Thermophilic crops* in Chinese oases not only indicates that they have a sensitive response to climate change, but also the different responses to climate change in different oasis areas. This reflects the regional differences in response to global warming by *Thermophilic crops*. This difference is mainly affected by different latitudes, basins, plateau topography, altitude and so on, which is better reflected in the individual characteristics of each oasis and the great difference in the response of warm crops to climate warming between southern Xinjiang oasis and Qaidam oasis.

(2) The end date of growth of *Thermophilic crops* was delayed significantly in China, and the change tendency rate was 0.148d/a. This is consistent with the study of the average trend of delayed end date of growth rate of 0.18±0.38d/a in 70% of the Northern Hemisphere [51]. From 1960 to 2016, the growth period of *Thermophilic crops* in Chinese oasis was prolonged by 16.7 days, which was larger than that of the previous studies, which showed that the length of growing season in 1955-2000 and 1961-2000 in China increased by 6.9-8.7 days and 6.6 days, respectively, growth period increased by 8.0-10.1 days [52-53]. This may be mainly due to the annual average annual surface temperature warming rate of 0.22℃/10a in China [54] and 0.42℃/10a in northwest China [55], which is 1.9 times higher than 0.22℃/10a in China. The results are consistent with the results of high 5.7 or equivalent conclusion that the growth season length of 1959-2008 and 1961-2010 increased by 11 days and 13.0-17.0 days, respectively, in the three northeastern provinces and Inner Mongolia at the same latitude [56-57]. According to the response of temperature, the average phenology of spring in Europe and oasis in China is 2.5 days and 4.83 days respectively for each temperature rise of 1℃ [58]. Obviously, the response of *Thermophilic crops* in Chinese oasis to climate warming is more sensitive.

(3) In this study, linear trend method, inverse distance weighted (IDW), morlet wavelet analysis, correlation analysis and univariate regression analysis were used. It not only reflects the response characteristics of *Thermotropic crops* to phenology, but also reveals the mechanism and sensitivity of regional differences. Unfortunately, there is no phenological observation data in the study area, and the meteorological observation data has a short sequence of 57 years, which can only reflect the

characteristics of variation, space-time law, possible cause and sensitivity of more than half a century.

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