Spatial-Temporal Characteristics And Influencing Factors of Climatic Growth Period of *Chimonophilous Crop* In Hexi Oasis During 1960-2019

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Abstract

Based on the daily average temperature data of 6 meteorological stations in the Hexi Oasis, Gansu Province, where the *chimonophilous* crop distribution area is located from 1960 to 2019. The spatio-temporal characteristics and influencing factors of the starting and ending days of the growth period, the number of days, and the effective accumulated temperature (Abbreviated as EAT) of the growing period of the *chimonophilous* crop in the Hexi Oasis was analyzed by Using climate tendency rate, ArcGIS inverse distance weighted interpolation, Mann-Kendall test, Morlet wavelet analysis, principal component analysis and correlation analysis methods, etc. The results show that there are significant differences in the spatio-temporal changes in the climate growth period of the *chimonophilous* crop in the Hexi Oasis. It shows a trend of decreasing from southeast to northwest, except for Yongchang (the highest elevation and lowest temperature in Yongchang). The M-K test showed that the growth period termination date was the most sensitive response to climate warming. Wavelet analysis shows the climatic growth period changes of cool-loving crops in the study area coincide with the cycles of atmospheric circulation 2-4a, El Niño 2-7a and sunspot activity quasi-11a. The changes are affected not only by 74 atmospheric circulation factors, but also by geographic parameters such as latitude and altitude, and monthly average temperature. This study provides scientific decision-making and basis support for the development of food and crop security and the improvement of the ability to withstand disasters in the Hexi Oasis. At the same time, it is of important theoretical significance and practical value for coping with climate change and proposing countermeasures for disaster prevention and mitigation.

1. Introduction

Global warming has become an indisputable fact (IPCC, 2013; Zhao et al., 2018). The rate of warming of the global average surface temperature in the last hundred years is almost twice as high as since 1880 (Qin et al., 2014). The effects of climate change on global ecosystems are altering their natural processes (Piao et al., 2003), causing mutation in the timing and length of the starting and ending of the growing season in many parts of the globe (Rezaei et al., 2017). Therefore, the study of crop growing season response and adaptation to climate change has become an important element in the analysis of climate change impacts on agricultural production (Porter et al., 2005). It is evident that the impact of climate change on the temporal and spatial variability of crop growing season is obvious and extensive (Olmstead et al., 2011). In the last 100 years, the increase in global temperature has prolonged the crop growing season at mid and high latitudes, especially at high latitudes in the Northern Hemisphere (Liu et al., 2016). The response of crop growing period to temperature changes varies significantly among regions. The planting period, flowering, and maturity of cereal crops in central Europe are 1-3 weeks earlier. Their crop growth and development are controlled to a greater extent by temperature (Olesen et al., 2012). The crop growing period and the area of the suitable zone are also being extended and expanded in northern Europe (Falloon et al., 2010). During 1961-2000, sowing, emergence and harvest of maize in Germany advanced by 1.7 d/10a, 3.3 d/10a, and 1.3 d/10a, respectively (Chmielewski et al., 2004). In contrast, oats were more responsive to temperature increases, with maturity advancing by about 4 d for

each 1°C increase in temperature (Estrella et al., 2007). In the United States, corn sowing was 10 d earlier, the growing season was 12 d longer, and cumulative temperatures were 14% higher from 1981-2005 (Oteros et al., 2015). In addition, Lashkari et al. (2012) used the crop model CERES-Maize to simulate that future delayed maize sowing in northeastern Iran may allow maize to avoid heat stress at the end of growth and thus reduce the adverse effects of climate change on crop growth. While Moradi et al. (2014) used CM model-GCM high resolution data and simulated that the growing period of maize in Iran will be shortened and yields will decrease in the next 100 years. The analysis by Babel and Babel et al. (2015) found that planting maize in March-May in western Uganda would increase maize yields by 17.9% when the sowing period is 16 d earlier. The crop growing period in China has increased at a rate of 11.6d/10a over the last 20 years, with an advance of 0.79d in spring and a delay of 0.37d in autumn (Jiang et al., 2011). In the last 50 years, the trend of prolonged days of crops growing period in northern China reached 2.3d/10a, while the starting day of crops growing period in southern areas was 0.6d/10a earlier and the days of the growing period were prolonged by 1.3d/10a (Song et al., 2010). The planting, emergence, and dormancy periods of winter wheat in China were delayed by 1.5d/10a, 1.7d/10a, and 1.5d/10a, respectively; and the spring germination, tasseling, flowering, and maturity periods were advanced by 1.1d/10a, 1.2d/10a, 2.7d/10a, and 1.4d/10a, respectively (Xiao et al., 2015). The sowing periods of overwintering and spring crops in northwest China were pushed back and earlier, respectively (Deng et al., 2010). Wang et al. (2004) found that continuous warming and drying of the climate shortened the growing period of spring wheat and maize, and lengthened the growing period of cotton for Hexi oasis crops. In the last 30 years, warm and wet climate change in the Heihe River basin has shortened the growing period of spring wheat and lengthened the growing period of maize, significantly improving the quality and yield of temperature-loving crops (Ma et al., 2015). The sowing period of oilseed rape in Qinghai Province was advanced, the maturity was delayed and the growth period was extended (Zhu et al., 2008). In Ningxia, the number of days of crop growing period was extended from south to north, and the duration gradually increased (Yuan et al., 2011). The heat conditions in the "three rivers" basin in eastern Tibet are suitable for growing *chimonophilous crop* of barley and wheat, with early first days and late last days, and the growth cycle of crops is extended, in which the heat resource conditions at low altitudes are more favorable for crop growth (Wang et al., 2017).

The Hexi Corridor is located in the northwest arid zone, which is the connection point between the Mongolian steppe and the Qinghai-Tibet Plateau, and is a key part of the Silk Road Economic Belt. Since ancient times, it has been a significant route to communicate with the western region, and has developed numerous large and small oases, which is the main supply base of commercial food and an important ecological barrier in China (Wei, 2016). The changes in the start and end of the climatic growth period, the number of days and the EAT are considered as the "best indicators" of crop response to climate change (Chen et al., 2009) and the "diagnostic fingerprints" of global environmental changes (Root et al., 2003). Therefore, this paper explores the spatial and temporal variation characteristics of the climatic growth period of *chimonophilous crop* in Hexi Oasis from 1960 to 2019 to reveal the response of crops to climate warming in Hexi Oasis. This paper provides a scientific decision-making support for the development of food and crop security and disaster resilience in Hexi Oasis. It is of great theoretical and

practical significance to adapt and respond to climate change and to propose disaster prevention and mitigation measures.

2. Survey Of The Study Area

The Hexi Oasis is located at 35°36'N ~ 42°19'N, 85°02'E ~ 114°25'E. It extends From Wushaoling in the east to Ancient Yumen Pass in the west. It is about 1000 km long from east to west and 50~100 km wide from north to south (Fig.1). It has an area of $2.15 \times 10^5 \text{ km}^2$, accounting for about 60% of the province's area. The administrative area includes five prefecture-level cities: Wuwei, Jinchang, Zhangye, Jiuquan and Jiayuguan (Yao et al., 2020). The terrain is generally high in the south and low in the north, with the Qilian Mountains in the south and the corridor zone in the middle, with flat terrain. The topography of the Hexi oasis area is complex, with widespread desert and Gobi, and the main landform types are large pre-mountain flood fans and impact plains. Temperate continental arid climate, the average annual temperature 4 ~ 10 °C, the average precipitation 9.5 ~ 592.8mm, the average evaporation 1650 ~ 3500mm, the average annual wind speed 2.0 ~ 4.2m / s, the average number of sunshine hours 2800 ~ 3300h. The climate is arid, the sunshine time is long, and the sunshine resources are abundant. It has an arid climate, long sunshine hours, and abundant light resources, and is an important climate change sensitive area and fragile ecological environment zone. There are 3 independent endorheic river systems of Shule River, Hei River and Shiyang River developing from west to east in the region, and most of them are seasonal rivers, and there are 15 rivers with annual runoff is above $1 \times 10^8 \text{ m}^3$. The main soil is brown desert soil, gray brown desert soil, gray desert soil, light brown calcium soil and gray calcium soil arid soil type. The main vegetation is mostly represented by sand date, camel thorn, tamarisk, and poplar (Shen, 2001).

3. Information And Methods

3.1 Data sources

In this paper, the daily average temperature data of 1960-2019 from six surface meteorological stations located in the distribution area of *chimonophilous crop* in Hexi Oasis were selected from the China Meteorology Administration (CMA) (<https://data.cma.cn/en>); the elevation data (DEM) were SRTM with 30m resolution from the geospatial data cloud (<http://www.gscloud.cn>); the circulation data were selected from 74 circulation indices (month-by-month data from 1960-2019), including the Tibetan Plateau Index (TPI), cold air (CA), Asian Zone Polar Vortex Area Index (APVAI), Asian Zone Polar Vortex Intensity Index (APVII), annual average carbon dioxide emissions (CDE), West Wind Index (WCI), and Siberian High Pressure Index (SHI), derived from the National Climate Center of China Meteorological Administration, with the CDE index from the World Development Index Report database (<http://data.worldbank.org>).

3.2 Research Methodology

3.2.1 Determining the starting and ending dates of climate growth period

In this paper, the start and end date of the stable passage of the 0°C-threshold temperature is taken as the start and end date of the climatic growth period of *chimonophilous crop*, and the number of days between the start and end date is the number of days of the climatic growth period. The specific method is: using the 5-day sliding average method, when the sliding average lasts $\geq 0^{\circ}\text{C}$, the first date of the first 5 consecutive days with a sliding average $\geq 0^{\circ}\text{C}$ is selected as the start date of the climatic growth period of *chimonophilous crop*; when the sliding average lasts $\geq 0^{\circ}\text{C}$, the last date of the last 5 consecutive days with a sliding average $\geq 0^{\circ}\text{C}$ is selected as the end date of the climatic growth period of *chimonophilous crop* (Lan et al., 2012).

3.2.2 Calculation of EAT

The average daily temperature reaches the biological lower limit temperature above which the crop starts to grow, and the temperature above the biological lower limit temperature is called the active temperature. The effective temperature is the temperature that has an effect on crop growth, mainly the difference between the active temperature and the biological lower limit temperature, i.e., the sum of that part of the daily average temperature above the biological lower limit temperature. The EAT is the cumulative value of the temperature above the lower limit temperature (Mcmaster et al., 1997). The effective temperature is given by the equation:

$$T_e = T_i - B \quad (i=1,2,\dots,n) \quad \dots\dots (1)$$

Where: T_e is the effective temperature, T_i is the daily average temperature, B is the biological lower limit temperature of the crop (*chimonophilous crop* are 0), $T_i \geq B$, if $T_i < B$, then T_i is counted as 0. The formula for calculating the EAT is:

$$A_e = \sum T_e = \sum_{i=1}^n (T_i - B) \quad \dots\dots (2)$$

Where: A_e is the effective accumulated temperature (EAT).

chimonophilous crop in the text are those whose temperature required for growth and development must be $\leq 0^{\circ}\text{C}$, such as winter wheat, spring wheat, barley, potato, and rape (Su, 2000).

3.2.3 Inverse Distance Weight Interpolation (IDW)

The inverse distance weight interpolation method is a simple and commonly used deterministic spatial interpolation method. It is based on the principle of similarity and similarity as the theoretical basis, and the distance between sample points and interpolation points is used as the weight for weighted average,

and the weight coefficient is inversely proportional to the distance. If the value of the point to be estimated is denoted by v_e , then there are:

$$v_e = \sum_{j=1}^n w_j v_j \quad \dots\dots (3)$$

$$w_j = \frac{f(d_{ej})}{\sum_{j=1}^n f(d_{ej})} \quad \dots\dots (4)$$

where: n is the number of neighboring points involved in the interpolation point, and $f(d_{ej})$ is the weight function of the distance d_{ej} between the neighboring points (X_j, Y_j) and the point to be interpolated (X_e, Y_e) , where the inverse of the distance or the inverse square function of the distance are the two most commonly used functions (Tang, 2002).

3.2.4 Morlet wavelet analysis

Morlet wavelet is a powerful statistical analysis method. It can discriminate the magnitude of the multi-timescale periodicity contained in a time series and the distribution of these periods in the time domain. It is widely used in the field of geology to analyze the complex time patterns of various geological processes. The continuous wavelet transforms for an arbitrary function $f(t) \in L^2(R)$ is:

$$W_f(a, b) = |a|^{-\frac{1}{2}} \int_R f(t) \psi\left(\frac{t-b}{a}\right) dt \quad \dots\dots (5)$$

Where: $W_f(a, b)$ is called the wavelet coefficient; a is the scale scaling factor; b is the time translation factor; $\psi_a, b(t)$ is a family of functions from which $\psi(t)$ scales and translates, called continuous wavelets (Wei, 2016).

4. Results And Analysis

4.1 Temporal variation characteristics of the climatic growing period of chimonophilous crop

In the past 60a, the start date of the growing season of *chimonophilous crop* in Hexi oasis showed a more obvious trend of advancement (Fig. 2a). Its propensity to change was $-1.752d/10a$ ($a \geq 0.01$), with a correlation coefficient of 0.38 and a total advance of 10.512d for 60a. The average annual growing season start date was March 12. The earliest of these began in 2017, on February 20, and the latest began in 1976, on March 28, with a difference of 37 d. This may be due to the marked warming characteristics in the northwest (especially in 2017) as a result of global warming since 2000 (Liang et

al., 2018), which has led to a significant advancement trend in the start date of the climatic growing season of *chimonophilous crop* in the region.

In the past 60a, the climatic growth period end date of *chimonophilous crop* in Hexi oasis have shown a fluctuating trend of pushing back the growth period (Fig. 2b). It has a tendency rate to change of 1.734d/10a ($a \geq 0.01$), a correlation coefficient of 0.40, and a total 60a pushback of 10.404d. The average annual growth period end date was November 9, with the earliest ending on October 19, 1981, and the latest ending on November 23, 2011, with a difference of 35 d. This is more in line with the findings that the trend of delayed crop growth termination days reached 1.8 ± 3.8 d/10a in 70% of the Northern Hemisphere (Sun, 2014).

In the past 60a, the number of days in the climatic growing period of *chimonophilous crop* in Hexi oasis were significantly prolonged with a trend of 3.486d/10a ($a \geq 0.01$) (Fig. 2c) with a correlation coefficient of 0.55, reaching a significance level of 20.916d in total for 60a, with an average annual growing period day of 243d, which is basically consistent with the average of 247d for *chimonophilous crop* in the northwest (Wang, 2018) where the growing period The longest number of days was 266 d in 2017 and the shortest was 216 d in 1970, with a difference of 50 d. The tendency of the extension of the climatic growing period days of *chimonophilous crop* in Hexi was significant. This may be related to the greater fluctuation of the delayed end date of the growing period of *chimonophilous crop* in this region. It can be seen that the climatic growth period days of *chimonophilous crop* in Hexi are more sensitive to the response of global warming.

In the past 60a, the overall trend of the EAT of *chimonophilous crop* in Hexi Oasis showed a sharp increase (Fig. 2d), with a tendency rate of 91.381°C/10a ($a \geq 0.01$) and a correlation coefficient of 0.79, reaching a highly significant confidence level, with a total increase of 548.286°C in 60a and an average annual EAT of 3492°C, of which the maximum value was 3923.45°C in 2013 and the minimum value was 3162.83°C in 1976, and the difference between them was 760.62°C. This may be due to the fact that the Hexi Oasis belongs to the warm temperate zone and the temperature increases rapidly. This trend is basically consistent with the conclusion of Sun Yang et al. that the average growth rate of $\geq 0^\circ\text{C}$ active cumulative temperature in the arid zone of northwest China is 80°C/10a (Sun et al., 2010).

In conclusion, the climatic growth period of *chimonophilous crop* in Hexi oasis has shown a trend of earlier start date and later end date, longer growth period days and higher EAT in the past 60a, which is consistent with the findings of *chimonophilous crop* in northern China (Wang, 2018) and northwest China oasis (Zhang et al., 2020). Among them, the start date of the growing period of *chimonophilous crop* started the latest in 1970s and ended the earliest in 1970s and 1980s, which may be related to the relatively low temperature and relatively poor climatic conditions of the growing period of crops in northern China in the 1970s (Wang et al., 2008; Han et al., 2010), and is also more consistent with the conclusion of Guo et al. that the temperature was lower in the late 1960s and warmed significantly in the mid-late 1980s in northwest China (Guo et al., 2005). In contrast, after entering the 21st century,

especially since 2010s the strongest global warming impact of the 21st century has led to rapid warming, which resulted in the postponement of end date, significant extension of growing period days, and significant increase of EAT.

From the interdecadal changes table, the start date of the *chimonophilous crop* climate growth period in the Hexi Oasis showed an earlier trend after the 21st century (Tab.1).Among them, the advancement trend in 2010s is the most significant, with a change tendency rate of -25.889d/10a ($a \geq 0.01$), and the average starting date of the growth period is 3/6.The most significant postponement trend is the 1990s, with a change tendency rate of only 9.212d/10a, and the average starting date of the growth period on 3/12. The end date of the *chimonophilous crop* climate growth period showed a postponement trend in 1970s, 1990s, and 2000s. The postponement trend of the 1970s was the most significant, with a change tendency rate of 11.606d/10a ($a \geq 0.01$), and the average end date of the growth period was 11/6.The most significant advance trend was in the 1960s, with a change tendency rate of only -4.717d/10a, and the average end date of the growth period was 11/6.The number of days in the climate growth period of the *chimonophilous crop* was prolonged in 1970s, 2000s, and 2010s, while the number of days in the 1960s, 1980s, and 1990s was shortened. The most significant trend was in 2010s, with a tendency to change 22.040d/10a ($a \geq 0.01$), and the average number of days in the growing season was 252d, while the most significant shortening was in 1960s, with a tendency to change -10.737d/10a, and the average number of days in the growing season was 238d; the EAT in the growing season of *chimonophilous crop* showed an increasing trend except for 1960s. Among them, the 1990s showed the most significant increasing trend, with the tendency of change reaching 308.350°C/10a ($a \geq 0.01$) and the average EAT of 3450°C during the growing period, while the 1960s showed a decreasing trend of EAT, with the tendency of change reaching -172.720°C/10a and the average EAT of 3387°C during the growing period. (In the following table, the tendency rate and the amount of change are abbreviated as Pr and Ac respectively)

Tab.1 Interdecadal temporal variation in the climatic growth period of *chimonophilous crop* in Hexi oasis

Era	Start date		End date		Growing season		EAT	
	Pr	Ac	Pr	Ac	Pr	Ac	Pr	Ac
	d/10a	d	d/10a	d	d/10a	d	d/10a	d
1960-1969	6.02*	16	-4.717	0.5	-10.737	-16	-172.720**	-65
1970-1979	1.333	-5	11.606**	10	6.232	15	54.7359	51
1980-1989	1.293	-7	-3.061	-14	-4.030	-7	20.9225	73
1990-1999	9.212*	4	2.293	-4	-6.919	-8	308.350**	211
2000-2009	-3.240	-4	0.990	3	4.232	7	241.450**	220
2010-2019	-25.889**	-19	-2.990	-3	22.040**	15	162.080**	135

Notes: *, **denote $\alpha = 0.05$, $\alpha = 0.01$ levels of significance, respectively.

4.2 Spatial variation characteristics of the climatic growth period of chimonophilous crop

In this paper, we use the inverse distance weighted interpolation method in ArcGIS 9.3 to map the spatial variation characteristics of the start and end days, number of days, and EAT of the climatic growing period of *chimonophilous crop* in Hexi oasis in the past 60 years, and explore the spatial distribution characteristics and patterns. The results showed that:

The spatial distribution of the start date of the growing season of *chimonophilous crop* in Hexi oasis varied significantly (Fig.3a), except for Yongchang, which had a trend of decreasing the number of days in advance from southeast to northwest. Earliest and the latest start dates from 3/8 to 3/22, with an extreme difference of 14 d. The earliest start date of the growing season in Wuwei was 3/8, followed by Gaotai and Minqin, with the start dates of 3/9 and 3/10, respectively, and followed by Jiuquan and Zhangye, while the latest start date of the growing season in Yongchang was 3/22. This is due to the fact that Yongchang is mainly affected by non-zonal factors, with a higher elevation (close to 2000m), which is significantly higher than the elevation of the other five sites by about 445-645m (Meng et al., 2012), and lower temperature, and the area is located in the "bee's knees" zone of the Hexi Corridor, which has a medium-temperate continental arid climate. The geological terrain of the territory is complex and varied, with rolling hills, an arid climate, scarce rainfall, and large sandy winds in winter and spring, which are not conducive to crop growth.

The spatial climatic end date of the climatic growth period of *chimonophilous crop* in Hexi oasis (Fig.3b), except for Yongchang, has a tendency to end earlier from southeast to northwest. The extreme difference is 10 d between 11/3 and 11/13. The end of the growing season in Yongchang was the earliest on 11/3, followed by Jiuquan and Zhangye, while the end of the growing season in Wuwei was the latest on 11/13, followed by Gaotai and Minqin on 11/11 and 11/10, respectively.

The spatial distribution of the number of days in the growth period *chimonophilous crop* in Hexi Oasis varied significantly (Fig.3c), except for Yongchang, which has a trend of gradually shortening growing period days from southeast to northwest. The number of growing period days ranged from 226 to 250 d, with an extreme difference of 24 d. The longest growing period days was 250 d in Wuwei, followed by 248 d and 246 d in Gaotai and Minqin, respectively, while the shortest was 226 d in Yongchang.

The difference in the spatial distribution of EAT of the *chimonophilous crop* in Hexi oasis reached a highly significant level (Fig.3d), with the EAT ranging from 2776°C to 3814°C with an extreme difference of 1038°C. The EAT of Minqin was as high as 3814°C, which was the highest, followed by Gaotai, Wuwei, Zhangye and Jiuquan, while Yongchang was the lowest at 2776°C. This is because Minqin is surrounded by Badanjilin and Tengger Desert on the north, east and west sides, and the continental desert climate features are very prominent, with sufficient light, scarce precipitation, large temperature difference between day and night, faster heat absorption on the lower cushion surface, and more rapid air warming, thus making Minqin's EAT increase.

In summary, there are significant differences in the growth period of *chimonophilous crop* in the Hexi Oasis. Among them, the Wuwei growth period has the earliest start date and the latest end date, the corresponding growth period has the longest number of days, and the EAT is the highest. Followed by Gaotai and Minqin respectively, while Yongchang is the opposite, with the latest start date and the earliest end date, the shortest growing period days and the lowest EAT.

4.3 Mutation analysis

In this paper, the Mann-Kendall test (Wei, 2016) was used to detect mutations in the starting and ending days of the growing period, the number of growing period days, and the EAT of the climate of *chimonophilous crop* in Hexi oasis in the past 60a. The mutation year was determined given a significance level of 0.05 and a critical value of ± 1.96 . The results showed that:

In the past 60a, the UF curve of the start day of the climatic growing season of *chimonophilous crop* in Hexi oasis is fluctuating and decreasing (Fig.4a), and the UF and UB curves of the Mann-Kendall test intersected in 2008 and 2012 at a significance level of 0.05. Therefore, the start day of the climatic growing season of *chimonophilous crop* in Hexi oasis is abruptly changed in 2008 and 2012, and the climatic start day of *chimonophilous crop* is more sensitive to climate change. The start date of the growing season of *chimonophilous crop* in Hexi oasis was more sensitive to climate change than the mutation year 1997 (Wang, 2016), and the mutation year 1993 of the start date of *chimonophilous crop* in Hexi oasis studied by Zhang et al. (Zhang et al., 2020). The start day of the climatic growth period of *chimonophilous crop* in Hexi oasis was on average on 3/13 and 3/13 before the mutation, respectively. After the mutation, start day of the climatic growth period of *chimonophilous crop* in Hexi oasis was advanced to 3/6 and 3/1, respectively, and start day of the climatic growth period of *chimonophilous crop* in Hexi oasis was advanced by 7 d and 12 d earlier than before the mutation, respectively.

In the past 60a, the response of the climatic end date of *chimonophilous crop* in Hexi oasis was the earliest, and the UF curve showed an increasing trend (Fig.4b), reaching a confidence level of 0.05. The UF and UB curves of the Mann-Kendall test intersected in 1983, 1990, and 1993, respectively. This is consistent with the abrupt change in the end date of *chimonophilous crop* in Hexi oasis in 1980, the abrupt change in the end date of the oasis in China in 1990 (Zhang et al., 2020), and also with the dramatic warming in China in the mid-late 1980s (Han et al., 2010). In conclusion, China's *chimonophilous crop* are most sensitive to climate warming at the end of their growth period. Before the mutation, the end dates of the *chimonophilous crop* climate growth period in Hexi Oasis were on 11/7, 11/7, and 11/6, respectively. After the mutation, it was 11/11, 11/12, and 11/13. After the mutation, the end date of the *chimonophilous crop* climatic growth period was delayed by 5d, 6d, and 7d, respectively.

The UF curves of the climatic growing period days of *chimonophilous crop* in Hexi oasis fluctuated upward (Fig.4c) and reached a significance level of 0.05. The UF and UB curves of the Mann-Kendall test intersected in 2000, so the climatic growing days of *chimonophilous crop* in Hexi oasis were significantly longer after 2000, which is consistent with the findings of 1997 (Zhang et al., 2020), the year of the mutation in the growing period days of *chimonophilous crop* in Hexi and Chinese oases. The average

number of days of climatic growing period before the mutation was 238 d, and after the mutation was 252 d. The number of days of climatic growing period of *chimonophilous crop* after the mutation was 14 d longer than before the mutation.

The UF curves of the climatic EAT of *chimonophilous crop* growing season in Hexi Oasis fluctuated upward (Fig.4d) and met the significance level of 0.05. The UF and UB curves of Mann-Kendall test intersected in 2003, so the climatic EAT of *chimonophilous crop* growing season in Hexi Oasis changed abruptly in 2003, and the climatic EAT of *chimonophilous crop* growing season after 2003 was significantly The EAT of *chimonophilous crop* climate in China and Northwest China was more sensitive to warming in 1995 and 1997, the year of mutation (Wang, 2018); before the mutation, the average EAT of *chimonophilous crop* climate in Hexi Oasis was 3393°C, and after the mutation, it was 3761°C, and the EAT of *chimonophilous crop* climate increased by 368°C after the mutation compared with that before the mutation.

In conclusion, the end date of the climatic growth period of the *chimonophilous crop* in the Hexi Oasis has the earliest and most sensitive response to climate warming, followed by the number of days and the EAT of the growing period, and the start date is slightly later in the past 60 years. It is mainly related to the fact that autumn is more sensitive to climate warming than spring (Zhang, 2011), which coincides with the conclusion of Meng Xiuqing et al. that autumn contributes more to the annual value of warming in the Hexi Oasis than spring (2012).

4.4 Period analysis

In this paper, the Matlab-Morlet wavelet power spectrum (WPS) analysis method (Wei, 2016) was used to test the variance and period analysis of the period of the start and end of the growing period days, the number of growing period days, and the EAT of the climatic growing period of *chimonophilous crop* in Hexi oasis. The results showed that:

There are mainly cycles of about 2.4a, 4.3a, and 8.6a in the starting days of the climatic growing period of *chimonophilous crop* in Hexi oasis, among which the cycles of 2.4a and 4.3a passed the 95% red noise significance test. The highest peak of 4.3a was the first main cycle, and 2.4a was the second main cycle. It has been strongly expressed during 1960-2019, with peaks in energy density mainly in 1990s and 2010s. The 2.4a and 4.3a cycles are consistent with the 2-4a cycle of the quasi-atmospheric circulation.

There are mainly cycles of about 2.6a, 5.1a, and 8.6a in the ending days of the climatic growing period of *chimonophilous crop* in Hexi oasis. The peak of 5.1a is the first main cycle of the series, and it has been oscillating strongly in 1960-2019. The continuous wavelet transform shows that there are oscillation periods of 2-8a throughout the study period, of which the periods of 2.6a, 5.1a, and 7.0a pass the red noise test for the oscillation cycles during the mid-1970s and 2008. 2.6a, 5.1a, and 7.0a are consistent with the quasi-atmospheric circulation 2-4a and El Niño 2-7a periods, respectively, indicating that the end date is also influenced by El Niño influence.

The climatic growth period days of *chimonophilous crop* in Hexi oasis mainly exist around 2.7a and 7.8a cycles, among which 2.7a cycle passes 95% red noise significance test. 15.1a cycle has the strongest oscillation as the first main cycle, because the sequence nearly 60a is too short to be reliable, 2.7a is the second main cycle. The peak of energy density is mainly concentrated in 1975s and 1990-2010.

There are mainly cycles of about 8.4a, and 11.8a in the EAT of the climatic growing period of *chimonophilous crop* in Hexi oasis. The 11.8a cycle is more consistent with the sunspot 11a cycle, but both of them failed the 95% red noise significance test, indicating that the cycle of EAT change during the growing season of *chimonophilous crop* in Hexi oasis is not obvious.

Since the short cycles ranging from 2.4 to 4.3a are consistent with the 2-4a cycle of atmospheric circulation, and the 2.4-7.0a cycle is more consistent with the 2-7a quasi-cycle of El Niño. It indicates that the starting and ending days of the growing season and the number of days in the growing season of *chimonophilous crop* in Hexi oasis are mainly affected by atmospheric circulation and El Nino, and the EAT is mainly influenced by solar activity.

4.5 Causal analysis

4.5.1 Influence of atmospheric circulation

In order to further analyze the main influencing factors of the climate change of the *chimonophilous crop* in the Hexi Oasis, this paper explores both natural and anthropogenic factors and selects the Tibetan Plateau Index (TPI), Cold Air (CA), Asia Polar Vortex Area Index (APVAI), Asia Polar Vortex Intensity Index (APVII), Average Annual Carbon Dioxide Emissions (CDE), Westerly Index (WCI), Siberia the high-pressure index (SHI) were linearly correlated with the starting and ending days of the growth period, the number of days, and the EAT of the growing period of the *chimonophilous crop* climate in the Hexi Oasis. In order to analyze the main influencing factors and test the results of the cycle analysis, as well as to reflect the relationship between the *chimonophilous crops* and the atmospheric circulation in the study area (Tab.2). The correlation analysis showed that the start days of the growing period of *chimonophilous crop* in Hexi oasis was mainly influenced by WCI and APVAI, with correlation coefficients of 0.409 and 0.377 ($a \geq 0.01$), respectively, while CDE, SHI and APVAI were well correlated with the end days of the growing period, with correlation coefficients of 0.368 ($a \geq 0.01$), 0.258 and -0.256 ($a \geq 0.05$). In addition, the number of growing days and EAT were highly significantly correlated with CDE, WCI, TPI and APVAI with correlation coefficients of 0.442, 0.403, 0.353, -0.459 and 0.809, 0.372, 0.414, -0.456 ($a \geq 0.01$), respectively. Among them, CDE has a significant high correlation with EAT, and the excessive emission of CO₂ is the main cause of global warming. It can be seen that the changes in crop growth season are very sensitive to the response of Hexi Oasis climate change (Zhang et al., 2017). Different crop growth periods have different sensitivity to the atmospheric circulation Index (ACI) response, but they all have a close relationship with the atmospheric circulation Index (ACI), which further proves the reliability and consistency of the cycle analysis. The above significant correlations are mainly due to the narrow northwest-southeast trending zone of the Hexi Oasis Corridor in Gansu Province, which has a variety of landscape types, complex and

diverse climate change, and extremely numerous influencing factors, and there are internal regional differences, which is basically consistent with the studies of Chai Zhonghua (2016) and Zhang et al. (Zhang et al., 2017).

Tab. 2 Correlation analysis between the start and end date, climate growth period and EAT of *chimonophilous crop* of influencing factors in Hexi oasis

Circulation factor	TPI	CA	APVAI	APVII	CDE	WCI	SHI
Start date	-0.248	-0.116	0.377**	-0.076	-0.235	-0.409**	0.069
Eed date	0.236	0.085	-0.256*	-0.08	0.368**	0.151	0.258*
Growing season	0.353**	0.146	-0.459**	-0.006	0.442**	0.403**	0.148
EAT	0.414**	0.154	-0.456**	0.01	0.809**	0.372**	0.0719

Notes: *, **denote $\alpha = 0.05$, $\alpha = 0.01$ levels of significance, respectively.

4.5.2 Influence of geographical parameters

Since the Hexi oasis shows a certain decreasing pattern from southeast to northwest, and the topography is highly undulating, the effect of latitude and altitude on the climatic growing period of *chimonophilous crop* is further analyzed in this paper. A binary linear regression model (99% confidence level, R^2 values are 0.92, 0.88, 0.91 and 0.97 respectively, while F values are 17, 11, 15 and 47, which are all greater than $F_{0.01}(2,54) = 4.98$) was developed for the start and end of the growing period of *chimonophilous crop*, the number of growing period days and EAT with latitude and altitude:

$$Y_1 = 1.84X_1 + 0.023X_2 - 34.22$$

$$Y_2 = -2.65X_1 - 0.017X_2 + 442$$

$$Y_3 = -4.49X_1 - 0.040X_2 + 477$$

$$Y_4 = -131.77X_1 - 1.701X_2 + 11205$$

Where: Y_1 , Y_2 , Y_3 and Y_4 are the start date, end date, number of growing days and EAT of *chimonophilous crop* in Hexi Oasis, respectively; X_1 is the latitude; X_2 is the altitude. The above model reflects that for every 1° of latitude to the north, the start date is delayed by 1.84 d, the end date is advanced by 2.65 d, the number of growing period days is shortened by 4.49 d, and the EAT is reduced by 131.77°C ; for every 100 m of altitude rise, the start date is delayed by 2.3 d, the end date is advanced by 1.7 d, the number of growing period days is shortened by 4.0 d, and the EAT is reduced by 170.1°C . This is consistent with the conclusion of the previous mutation analysis that the climatic growth period end date is the most sensitive to climate warming response, and similar to the conclusion of Wang Tianqiang (2018) that the

climatic growth period days of *chimonophilous crop* in northwest China are more significant than the starting date due to the influence of latitude and altitude.

4.5.3 Influence of monthly average temperature

Temperature is the dominant meteorological factor affecting the crop growing period (Zhang, 1995). In this paper, the following regression equations were established by regressing the start date, end date, number of days in the growing season and EAT of *chimonophilous crop* in Hexi oasis with the mean temperature in March, November and March-November of the corresponding months (99% confidence level, R^2 is 0.98, 0.95, 0.91 and 0.99, respectively, and F is 182, 57, 39 and 1387, respectively, which are all greater than $F_{0.01}(2,54) = 4.98$):

$$Y_1 = -4.11X_3 + 81.80$$

$$Y_2 = 4.10X_4 + 316.26$$

$$Y_3 = 5.60X_5 + 172.68$$

$$Y_4 = 251.91X_5 + 330.84$$

Where: Y_1 , Y_2 , Y_3 and Y_4 are the start date, end date, number of growing days and EAT of *chimonophilous crop* in Hexi Oasis, respectively; X_3 is the average temperature in March; X_4 is the average temperature in November; X_5 is the average temperature from March to November. The regression model results showed that if the average temperature in March increased by 1°C, the start date of the growing period of *chimonophilous crop* in Hexi Oasis would be 4.11 d earlier; if the average temperature in November increased by 1°C, the end date would be 4.10 d later; if the average temperature in March-November increased by 1°C, the number of growing period days would be 5.60 d longer and the EAT would be 251.91°C higher. This is consistent with the findings of the response relationship between growing season variation and temperature in poplar studied by Zhang et al. (Zhang et al., 2017), which shows that the response of *chimonophilous crop* in Hexi Oasis is very sensitive to global warming.

5. Discussion And Conclusion

5.1 Discussion

The potential impact of climate change on crop growing season is obvious and extensive, and global warming is the main cause of crop growing season changes (Rezaei et al., 2017), and the response of climatic growing season changes of *chimonophilous crop* in Hexi Oasis is also more sensitive to temperature. In this paper, we concluded that the start date of the climatic growing period of *chimonophilous crop* in Hexi Oasis is earlier, the end date is pushed back, the number of growing period days is longer, and the EAT is higher, which is consistent with the findings of previous studies. In this paper, the starting date of the growing season of *chimonophilous crop* in Hexi Oasis was earlier, the

ending date was later, the number of growing season days was longer and the EAT was higher by -1.752 d/10a, 1.734 d/10a, 3.786 d/10a and 91.381°C/10a, respectively, while the tendency of the starting date of the growing season of *chimonophilous crop* climate in the Chinese oasis was earlier by -1.21 d/10a, the tendency of the ending date was later by 1.61 d/10a, and the tendency of the starting date of the growing season of *chimonophilous crop* climate in the Chinese oasis was later by 1.61 d/10a(Wang, 2017). This reflects that the end date is more sensitive to global warming than the start date, and the *chimonophilous crop* in Hexi Oasis are more sensitive to global warming than those in the Chinese oasis. At the same time, the regional response was also different, showing strong regional characteristics. The climatic growth period of *chimonophilous crop* in Hexi Oasis showed a trend of gradually decreasing from southeast to northwest due to the influence of latitude, except for Yongchang. In contrast, the climatic growth period of *chimonophilous crop* in Yongchang area showed the latest starting date, earliest ending date, shortest number of days, and lowest EAT due to the influence of non-zonal factors (altitude), because the higher altitude and lower temperature in the area are not conducive to crop growth. In addition, Wang Tianqiang (2018) analyzed the factors influencing the climatic growth period variation of *chimonophilous crop* in terms of atmospheric circulation factors and geographical parameters, and Zhang et al. (Zhang et al., 2017) analyzed the factors influencing the climatic growth period variation of *chimonophilous crop* in terms of monthly mean temperature, etc. We conducted a factor analysis by looking at atmospheric circulation, latitude, altitude and March-November mean climate as well, and the results all showed significant correlations.

In this paper, we only selected the meteorological data of the stations in the distribution area in Hexi Oasis, and the study area is small, and the number of 6 sites is less, and the distribution of stations is not uniform. At the same time, due to the lack of phenological data, we did not compare and verify with the agricultural phenological observation data and experimental data, and we also lacked the index study of each stage of crop growth and development. In the follow-up research, we need to strengthen the observation of phenology, combine with remote sensing grid point data with the accurate analysis and the changes of plants, wind and cold temperature and extreme weather brought by the global warming, so as to better reveal the laws and mechanisms, and provide the basis and service for ensuring food security and promoting the development of efficient agricultural weather.

5.2 Conclusion

(1) In the past 60a, the climatic growth period of *chimonophilous crop* in Hexi Oasis has a trend of earlier start date, later end date, longer growth period days, and higher EAT, with the tendency rates of -1.752d/10a, 1.734d/10a, 3.486d/10a, and 91.381°C/10a, respectively.

(2) The climate of Hexi Oasis' *chimonophilous crop* has a significant spatial difference in the growth period. Except for Yongchang, it has a trend of decreasing from the southeast to the northwest. Among them, Wuwei has the earliest starting day, the latest ending day, the longest growing period days and the largest EAT of the growing period, while Yongchang has the highest altitude and the lowest temperature, showing a reverse trend.

(3) The mutation analysis showed that the starting and ending days, the number of days and the EAT of the growing period of *chimonophilous crop* in Hexi Oasis were significantly earlier in 2008 and 2012, significantly later in 1983, 1990 and 1993, significantly longer in 2000 and significantly higher in 2003, and obviously the response of the ending day was the most sensitive, followed by the number of days and the EAT of the growing period, while the response of the starting day was the latest. At the same time, the starting and ending days, the number of days of the growing period of *chimonophilous crop* have cycles of about 2~4a and 2~7a, and the EAT has a cycle of about 11a. Except for the EAT, which is influenced by solar activity, the rest are mainly influenced by the atmospheric circulation and El Niño.

(4) The correlation analysis showed that the start and end days, the number of growing season days and the EAT of *chimonophilous crop* climate growth period in Hexi oasis in the past 60a are mainly influenced by the Asian polar vortex area index, the average annual CO₂ emission, the westerly wind index and the Qinghai-Tibet Plateau index in the Asian region, all of which passed the 99% significance test, which is consistent with the cycle results derived from the Morlet wavelet analysis above, which not only further reveals the influence of atmospheric circulation, but also reflects the influence of human activities through CDE.

(5) The regression model shows that if the average temperature in March increases by 1°C, the start date of the climatic growing period of *chimonophilous crop* in Hexi Oasis will be 4.11d earlier; if the average temperature in November increases by 1°C, the end date will be 4.10d later; if the average temperature in March-November increases by 1°C, the number of growing period days will be 5.60d longer and the EAT will be 251.91°C higher. The study indicates that the climatic growth period changes of *chimonophilous crop* in Hexi Oasis are very sensitive to the response of global warming.

Declarations

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Author's Contribution

All authors contributed to the study conception and design. Data collection and analysis were performed by Juan Lu, Wangxiong Zhang and Lei Gao. The draft of the manuscript was written by Juan Lu. Puxing Liu commented on it for its improvement. All authors read and approved the final manuscript.

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Availability of data and material

The in-situ temperature data were provided by the China Meteorology Administration (CMA) (<https://data.cma.cn/en>). The elevation data (DEM) were SRTM with 30m resolution from the geospatial data cloud (<http://www.gscloud.cn>). The data are not available to the public due to legal constraints on the data's availability.

Code availability

We used the Matlab software.

Ethics approval

Not applicable.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Conflict of Interest

The authors declare no conflict of interest

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Figures

Figure 1

Distribution of meteorological stations in Hexi Oasis

Figure 2

Annual change of the climate growth period of chimonophilous crop in Hexi oasis

Figure 3

Spatial distribution of climate growth period of chimonophilous crop in Hexi oasis

Figure 4

Mutation analysis of the climate growth period of chimonophilous crop in Hexi oasis

Figure 5

Morlet wavelet analysis of the growth period of chimonophilous crop in Hexi oasis