Research article

Comprehensive climate factor characteristics and quantitative analysis of their impacts on grain yields in China's grain-producing areas

Jieming Chou [a], Yuan Xu [a,*], Wenjie Dong [b], Tian Xian [a], Hong Xu [a], Zheng Wang [c]

[a] State Key Laboratory of Earth Surface Processes and Resource Ecology, Faculty of Geographical Science, Beijing Normal University, Beijing, 100875, China
[b] School of Atmospheric Sciences, Sun Yat-Sen University, Guangdong, 519082, China
[c] College of Atmospheric Sciences, Lanzhou University, Gansu, 730000, China

ABSTRACT

Climate change elements are important indicators for assessing the impact of climate change on the agricultural economy. A Comprehensive Climate Factor (CCF) that is composed of three indicators, growing season mean temperature, precipitation and sunshine hours indicators was developed. These indicators are aggregated into a single index that is a measure of the sensitivity of regionally integrated climate change. This paper uses this factor to explore the integrated climate variations over China's grain-producing areas in 1981–2015, divide the areas into climate change-sensitive zones, and quantitatively assess the impact intensity of CCF variation on grain yield. The results indicate that the growing season mean CCF basically increased in most grain-producing areas. The climatic tendency of the North plate is greater than that of the South plate, reaching 0.52 decade^{-1}, and the South plate has a quasi-4a periodic variation. The patterns of the impact of climate change on grain yield show that the impact intensity of climate change gradually decreased in each decade (from 0.25 to 0.2) and was stronger in the southwest than in the northeast. This research can be applied to improve the accuracy of economic-climate model simulations and predictions and to provide a theoretical reference and scientific support for assessing the impact and risk of climate change.

1. Introduction

Responding to and resisting the potential negative impacts of climate change on food security is a major challenge facing humanity in the 21st century, and it is also a hotspot in academic research. Since the reform and opening up, the total grain output has shown a rising trend. Food production is affected by climate change and faces increasing risks against the backdrop of China's continued climate warming (Alexander et al., 2006; IPCC et al., 2014; C.M.A., 2018). Food security will be increasingly uncertain in the future (Cantelaube et al., 2004; Holst et al., 2013; Niles et al., 2015). China's grain-production areas are critical areas for ensuring national food security. From the perspective of economic development, it is useful to research the sensitivity and risk of climate change in typical areas. Understanding climate change in China's grain-producing areas is a prerequisite to addressing and adapting to the impact of climate change on grain yield. Exploring the climate change characteristics and the identification of climate-sensitive zones in grain-producing areas is urgently needed to address climate change risks during the growth season in China's grain-producing areas.

The growth and development of different grain crops are affected by different climatic factors in different regions. In the study of the impact of climate change on regional food production, many scholars have performed valuable work, and different studies have used different models and data to draw different findings and conclusions. Tang et al. (2000) used the general circulation model and the agro-ecological zone model to assess the impacts of temperature, precipitation and sunshine hours on China's agricultural production in the 2020s and 2050s and found that the increasing temperature and rainfall in northeastern and northwestern China had a positive influence on food production; conversely, the increasing temperature and decreasing rainfall in eastern, central and southwestern China had a negative influence on food production. Liu et al. (2004) used the Ricardian model to research the economic impacts of temperature and precipitation on China's agriculture and found that under most climate change scenarios, higher temperature and more precipitation would have a positive impact on agricultural production in east and central of China. Hui et al., 2005 used regional climate scenarios and crop models to assess the impact of precipitation on China's wheat yield in the 2070s and found that more precipitation in the future would

---
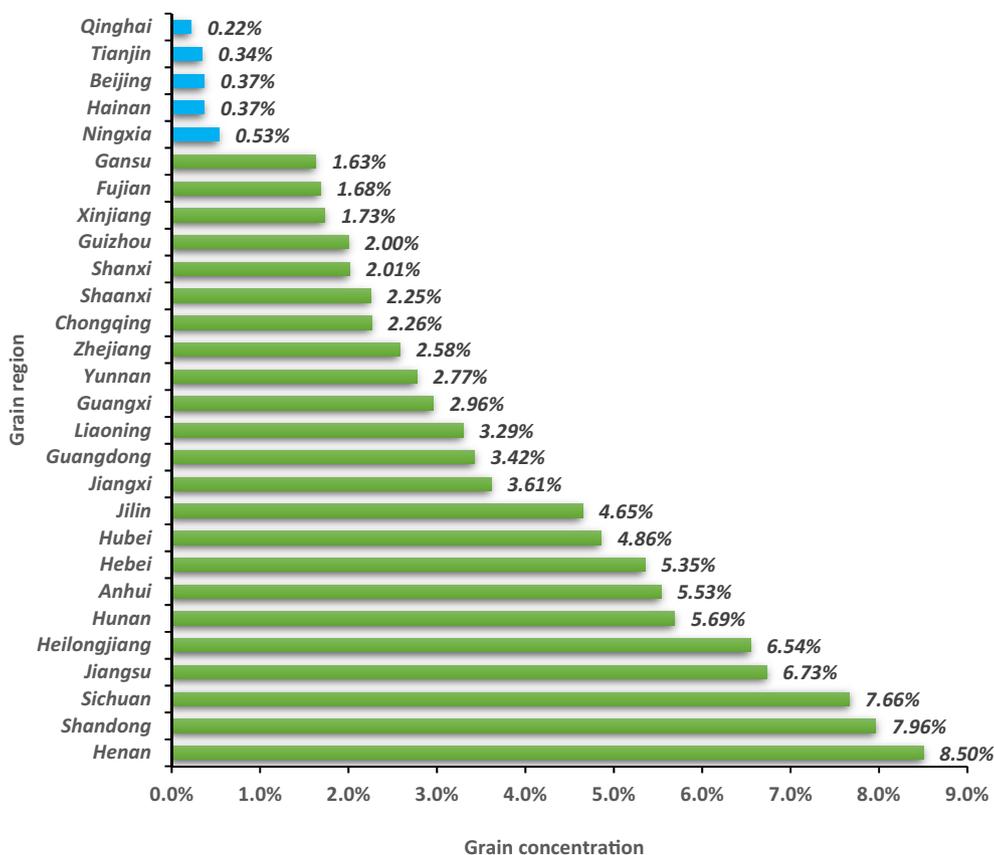
Fig. 1. Distribution of the annual mean grain concentration in the provinces (1981–2015) (Green bars indicate that the grain concentration is more than 1.00%, and blue bars indicate that the grain concentration is less than 1.00%.).

have an adverse impact on rainfed wheat yields. Chou et al. (2011) used the economic-climate model (C-D-C) to assess the impacts of climate change on grain yield and found that climate change in Northeast China, North China and Central China had a negative elasticity with regional grain yield. Holst et al. (2013) used a function model to analyze the impacts of temperature and precipitation on China's grain yield and found that a 1 °C increase in the annual mean temperature could reduce national grain output by 1.45% and that an increase in the total annual precipitation of approximately 100 mm could increase national grain output by 1.31%. Xiong et al. (2014) used multiple regression models to explore the effects of growing-season climate warming on the different crop yields in China and found that maize, wheat and soybean had significant negative yield responses to high growing-season mean temperature. Previous studies have focused on the impact of different climatic factors on different kinds of crops in different regions, but the research on targeted exploration of grain-production areas as typical areas is still incomplete. At the same time, most studies have focused on the study of single climatic factors, while comprehensive research on multiple climatic factors in a region is still lacking. In fact, the growth and development of crops is not an independent impact of a single climatic factor but is an integrated effect of multiple climatic factors. At present, research on comprehensive climatic factors requires further exploration. Therefore, this study constructed the main climatic factors (i.e., air temperature, precipitation, and sunshine hours) into a Comprehensive Climate Factor and quantitatively analyzed the impacts of integrated climate change in China's grain-producing areas. This is a creative research method that combines complex factors in order to study main trends. Assessing the characteristics of integrated climate change in the growth season and introducing climate change factors into models (e.g., the economic-climate model) to assess the impact of climate change on food production in the future are thus crucial for decisions related to

climate change mitigation.

Identifying the climate change zones of grain-producing areas is an important way to study climate change and its influence in agricultural regions. Climate change-sensitive areas are the main driving force behind food production risks, and identifying these areas is of great significance for adapting to climate change (Giorgi, 2006; Wu et al., 2012; Wu et al., 2017; Li et al., 2018). The Comprehensive Climate Factor would serve as a new indicator to supplement single climate elements and facilitate the identification of climate change-sensitive zones and the further study the impact of climate changes on food production.

In this study, we addressed the issues of changes in the Comprehensive Climate Factors during the growth season. The objectives of this study were (1) to construct a comprehensive climate change indicator that reflects the sensitivity of grain output, (2) to determine the changes in integrated climate variability, (3) to reflect the spatial sensitivity of

Table 1
The division and distribution of China's grain-producing areas.

Plate	Area	Province	Location
North Plate	Northeast China (NEC)	Liaoning, Jilin, Heilongjiang	Approximately 30°-50°N
	North China (NC) Northwest China (NWC)	Hebei, Shanxi, Shandong Shaanxi, Gansu	70°-140°E
	Xinjiang	Xinjiang Uygur Autonomous Region	
South Plate	East China (EC)	Jiangsu, Zhejiang, Anhui	Approximately 10°–30° N
	South China (SC)	Guangdong, Fujian	100°-120°E
	Central China (CC)	Henan, Hubei, Hunan, Jiangxi	
	Southwest China (SWC)	Sichuan, Yunnan, Chongqin, Guizhou、 Guangxi Zhuang Autonomous Region	
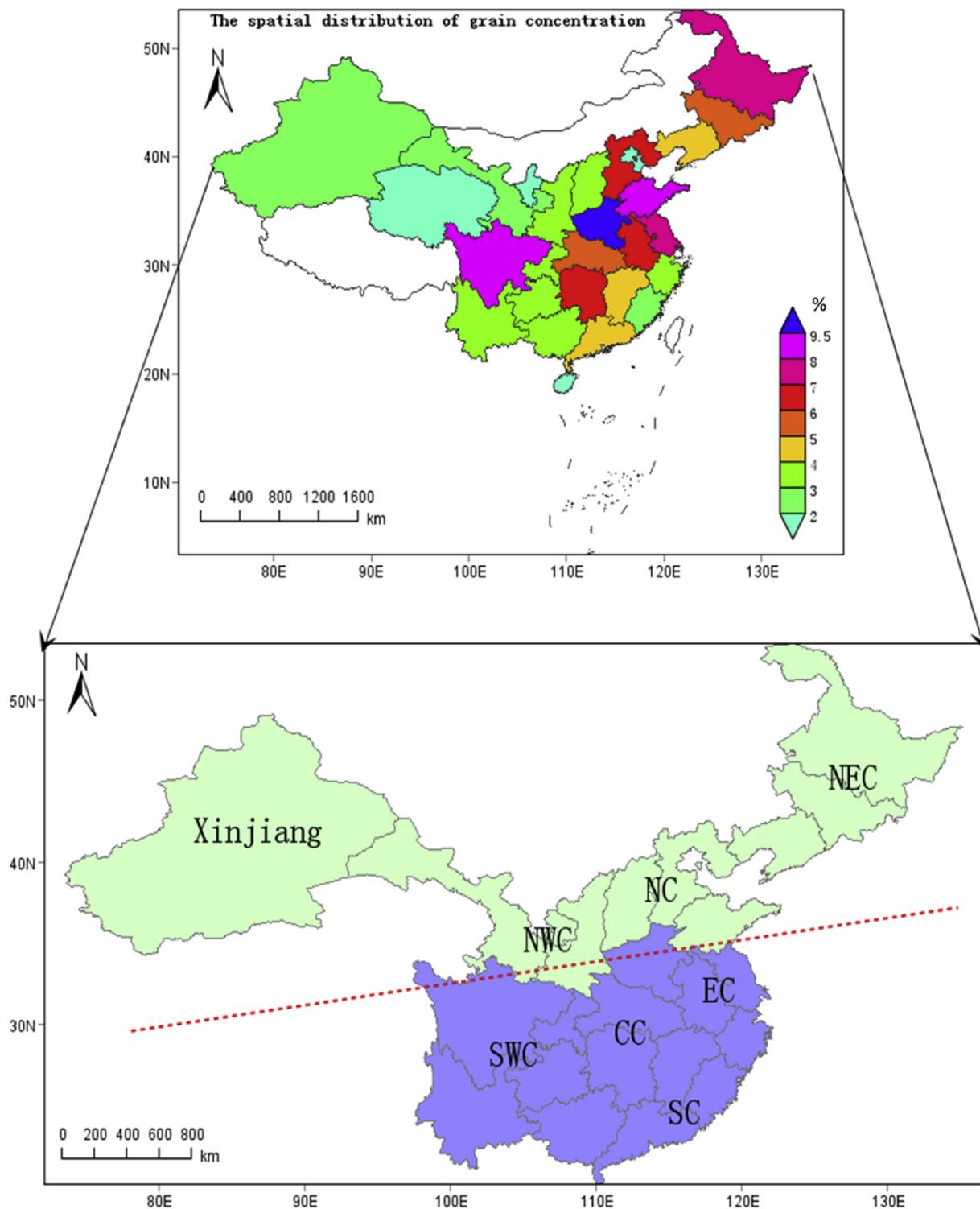
Fig. 2. Distribution of China's grain-producing areas (The dotted line represents the approximate dividing line between the North and South plates, and the letters are abbreviations of the grain-producing areas in Table 1.).

this climate change, and (4) to assess the impact intensity of climate change on food production.

2. Research area and data method

2.1. Data sources and preprocessing

The climate data were obtained from the Climate Dataset of the China Meteorological Data Service Center (http://data.cma.cn) and the China Meteorological Administration, and they included the monthly precipitation (unit: mm), mean air temperature (unit: Kelvin) and sunshine hours (unit: hour) recorded at 140 stations across China from 1981 to 2015 during the growth season (April–September).

Since the original data were monthly station data, with regards to the data processing, we performed the following steps:

Step 1. The average values of the monthly station data over 6 months (April–September) were used as the growing season station data.

Step 2. The station mean values of growing season station data for

each province were used as province data. The data for the eight grain-producing areas and two plates were obtained by the statistical method of the area-weighted mean.

Step 3. The data from Step 2 were all standardized to obtain the standardized growing season data for the climatic factors.

2.2. Identification of China's grain-producing areas

The grain production concentration in each region refers to the proportion of grain production in a certain region at a certain time to the total grain output of the country. It is generally used to measure regional food production, and its changes can reflect the status change of the region in terms of national food production (Lu an Mei, 2007). Considering that climate change represents an average change state over many years, in order to unify the time scale, this paper used the annual mean grain yield to calculate the annual mean grain-production concentration (AMGPC).

The criteria for the identification of grain-producing areas were based on the following: (i) The agricultural economic indicator, grain-production concentration: Fig. 1 showes the distribution of the AMGPC of the 28 provinces in China. The data were derived from the statistics of the National Bureau of Statistics of China (http://data.stats.gov.cn). From 1981 to 2015, the national annual mean grain yield was about 470 million tons. A province with an AMGPC of more than 1.00% has an annual mean grain-production level of at least 7.6 million tons, while a province with an AMGPC of less than 1.00% has an annual mean grain-production level of less than 2.5 million tons. Therefore, this paper used an AMGPC of 1.00% as the threshold for identifying the grain-production areas. The 23 provinces with AMGPC more than 1.00% were identified as grain-production areas, and their annual mean grain yields accounted for 95.7% of the nationwide grain yield. (ii) China's agricultural regionalization rule: agricultural development is closely related to government leadership and policy implementation. Statistical data are compiled by administrative region. On the basis of the eight grain-production areas divided by the "China Comprehensive Agricultural Regionalization" program (Liu et al., 2009), this paper maintained relative consistency between agricultural regions and administrative regions and identified the eight new grain-production areas. (iii) Differences in climate characteristics between southern and northern China: the Qinling-Huaihe line was used as the north-south boundary line in China. The northern and southern areas were divided into the climate change sensitive zones in China (Yan and Zheng, 2001; Liu et al., 2009; Zhang et al., 2012).

In summary, the specific divisions and distribution of China's grain-production areas are shown in Table 1 and Fig. 2.

Chou et al. (2019) used a geographical detector to analyze the North-South regional division of China's main grain-producing areas with spatial stratified heterogeneity (SSH). The q-value in the geographical detector measures the differentiation of the main grain-production areas

and can explain the geographical phenomenon that the variance within the region is smaller than the interregion variance. The larger the q-value is, the more obvious the SSH of the variable, and the greater the contribution of the corresponding impact factor. Therefore, this paper used the geographical detector to identify the division of the North and South plates based on the growing season mean temperature, precipitation and sunshine hours, and used the q-value to obtain the influence degrees of the different climatic factors on the zoning of grain-producing areas. The factor detector of the geographical detector found that the q-values of precipitation and sunshine hours were higher (q_{Pre}=0.836, q_{Sun} = 0.838). This illustrated that there was significant spatial heterogeneity in the climate characteristics and the grain-producing level between the North and South plates, that is, the division of the North and South plates had a certain rationality and reference value.

2.3. Research methods

In this paper, principal component analysis was used to incorporate the mean temperature, precipitation and sunshine hours into the Comprehensive Climate Factor (CCF). The climatic tendency and wavelet analysis methods were used to explore the climate variations characteristics of CCF, and then the impact intensity of climate change on grain yield was assessed by a geographical detector model. The detailed methods are described below.

2.3.1. Principal component analysis

Principal component analysis (PCA) can replace original indicators with fewer indicators and comprehensively reflect information produced from more indicators (Huang, 2004; Brunetti et al., 2006). Suppose that there are n sites in a climatic field and that each station has p climatic elements, i.e., there is a climatic field such as

$$X = \left(x_{ij}\right)_{pn} \tag{1}$$

Suppose that there is a new variable Y that satisfies $Y=VX$. Then, $Y = (y_{ij})_{pn}$ is the main component. In the formula, $V = (V_{ij})_p$ is a feature vector obtained from the correlation matrix of climatic field X. In general, when the cumulative contribution of the current principal component (m) variance ($G(m)$) ≥ 80%, the first m principal components can reflect the main information and characteristics of the entire climatic field.

2.3.2. Morlet wavelet analysis

The wavelet analysis method can analyze the periodic components contained in climate data, fully reflecting the trends of climate systems on different time scales (Dai and Chou, 1995; Jung et al., 2002). The principles and methods of wavelet analysis were described in previous results, and it was been found that Morlet wavelet analysis appropriately represents detailed features of time series data (Torrence and Webster,

Table 2
Statistical results of climate factors obtained by PCA for China's grain-producing areas.

Plate	Area	Z1	Z1%	Z2	Z2%
North	North Plate	1.87	62.3%	0.78	25.9%
Plate	NEC	1.82	60.7%	0.82	27.6%
	NC	1.53	51.0%	1.09	36.3%
	NWC	1.62	53.9%	0.88	29.2%
	Xinjiang	1.94	64.6%	0.73	24.4%
South	South Plate	1.49	49.7%	0.99	32.8%
Plate	EC	1.90	63.3%	0.80	26.7%
	SC	1.92	64.1%	0.76	25.4%
	CC	1.60	53.4%	0.85	28.4%
	SWC	1.59	53.1%	0.84	27.9%
National		1.55	51.6%	0.98	32.8%

(Note: Z1 and Z2 represent the eigenvalues of the first and second principal components; Z1% and Z2% represent the variance contribution rates of the principal components).

Table 3
Simulation of the Comprehensive Climate Factor over China's grain-producing areas.

Plate	Area	Comprehensive Climate Factor Equation
North	North Plate	$C = 0.766*T + 0.392*P - 0.008*S$
Plate	NEC	$C = 0.314*T + 0.336*P + 0.822*S$
	NC	$C = 0.694*T + 0.270*P + 0.542*S$
	NWC	$C = 0.680*T + 0.420*P + 0.030*S$
	Xinjiang	$C = 0.395*T + 0.803*P + 0.015*S$
South	South Plate	$C = 0.398*T + 0.658*P + 0.141*S$
Plate	EC	$C = 1.460*T + 0.250*P + 0.339*S$
	SC	$C = 0.339*T + 0.906*P + 0.265*S$
	CC	$C = 0.690*T + 0.408*P + 0.003*S$
	SWC	$C = 0.695*T + 0.409*P - 0.004*S$
National		$C = 0.392*T + 0.697*P + 0.182*S$

(Note: T, P, S and C are the standardized temperature, precipitation, sunshine hours, and Comprehensive Climate Factor (dimensionless) during the growth season).
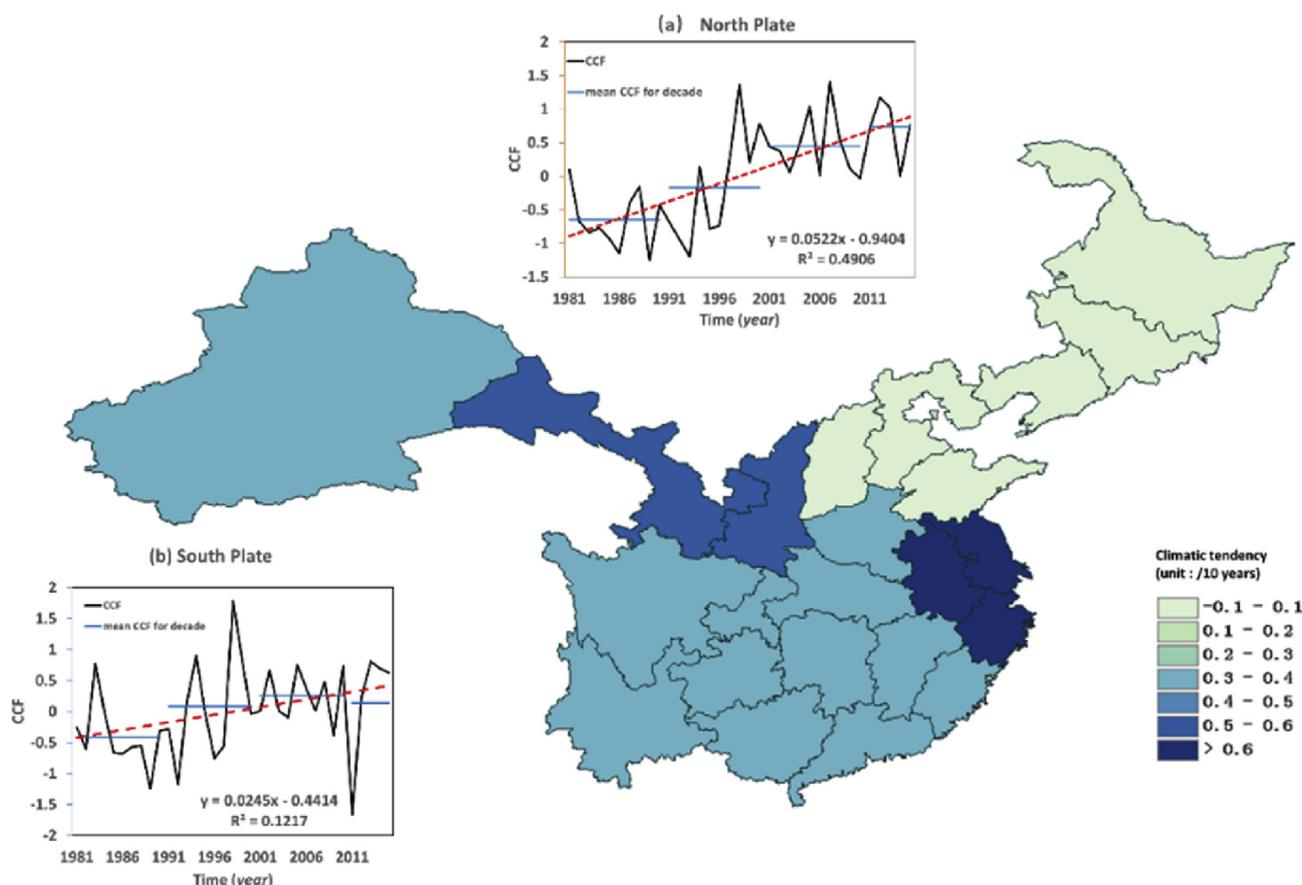
Fig. 3. Temporal and spatial patterns of variations in the Comprehensive Climate Factor in China's grain-producing areas (1981–2015) (The CCF climate tendency can clearly show the variation trend in CCF. In figure (a–b), the blue dotted line is the 10-year moving average of the CCF; the red dotted line in (a) is the linear trend of the CCF in the North plate: $y = 0.052x - 0.94$, $P < 0.05$; the red dotted line in (b) is the linear trend of the CCF in the South plate: $y = 0.025x - 0.441$, $P < 0.05$.).

1999; Qian et al., 2014; Gallegati, 2018). The formula is as follows:

$$\psi(t) = \pi^{-1/4} \; \exp(-i\omega_0 t) \; \exp\left(-t^2 / 2\right) \tag{2}$$

where ω_0 is a dimensionless constant ($\omega_0 \geq 5$).

2.3.3. Geographical detector model

The grain yield and its related influencing factors are spatially different. If the intensities of the influencing factors and grain yield are spatially significant, that is, if their q-values are high and the spatial heterogeneity is significant, it indicates that this factor is decisive in the changes in grain yield. A geographical detector is a statistical method for identifying the spatial stratified heterogeneity (SSH) of geographic elements and revealing the causes (driving forces) of the SSH. The principles and methods of the geographical detector were described by Wang et al. (2016); Wang and Xu (2017), and who found that the geo-detection index q-values of the influencing factors could not only explain the demarcation of geospatial space but could also explain the impact intensity of the influencing factors on grain yield. The q-value formula is as follows:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N \sigma^2} \tag{3}$$

where N is the number of units, σ^2 is the variance of Y, and Y is composed of L strata ($h = 1, 2, …, L$). N_h is the number of units, and σ_h^2 is the variance of Y in stratum h. The purposes of using the geo-detector to analyze the SSH of related influencing factors are: First, the zoning of the North and South plate (Fig. 2) is detected according to various climatic

factors to verify the rationality and scientificity of the zoning; The second is to quantitatively analyze the impact intensity of integrated climate factors on food production.

3. Analysis and results

3.1. Comprehensive climate factor establishment

The climatic resource conditions (i.e., temperature, precipitation and sunshine hours) are the basic conditions for grain production. The growth and development of crops are inseparable from the temperature, precipitation and sunshine hours. Additionally, crops are affected by these climatic resources. It is necessary to integrate multiple climatic factors into a new climatic factor that can reflect the main features of the elements. The standardized values of the growing season mean temperature, precipitation and sunshine hours were analyzed by PCA to construct a Comprehensive Climate Factor. The eigenvalues of the first two principal components and their variance ratios were obtained (Table 2).

The cumulative variance ratios of the first principal component and the second principal component in each area exceeded 80% (Table 2). This indicated that the first two principal components in each area could explain most of the local climate characteristics. The corresponding eigenvalue in each area was used as the weight, and the first two principal components were weighted to construct a Comprehensive Climate Factor (Table 3).

The paper defined the Comprehensive Climate Factor (CCF) as an integrated statistical indicator consisting of various climatic factors (i.e., temperature, precipitation and sunshine hours) and its formula is

$$C = a_1*T + a_2*P + a_3*S \tag{4}$$

where *C* is the growing season mean CCF (dimensionless). *T, P* and *S* are the mean temperature (unit: °C), precipitation (unit: mm) and sunshine hours (unit: hour) during the growth season. a_1, a_2, a_3 are the weights corresponding to the climatic factor variables. The CCFs calculated by formula (4) could reflect local climate information (e.g., temperature, precipitation and sunshine). The original complex climate change information could now be used to discuss China's climate change and its regional sensitivity over the past 35 years using a CCF. Thus, there are advantages to creating a CCF.

The CCFs constructed by the PCA method are standardized variables. If the standardized value of the CCF was positive, the CCF anomaly was positive, which indicated that the CCF changes over time were large relative to the annual values. If the standardized value of the CCF was negative, the CCF anomaly was negative, which indicated that the CCF was abnormally small relative to the annual value.

3.2. Comprehensive climate factor variation characteristics

Based on the CCF equations in Table 3, the growing season CCF was calculated for 1981–2015. The characteristics of the trend changes and periodic variations were studied.

3.2.1. Comprehensive climate factor trend changes

Over time, the CCF showed a positive climate tendency in China's grain-producing areas. The variation in the CCF over the North plate showed a significant increasing trend, with a value of 0.52 decade^{-1}.
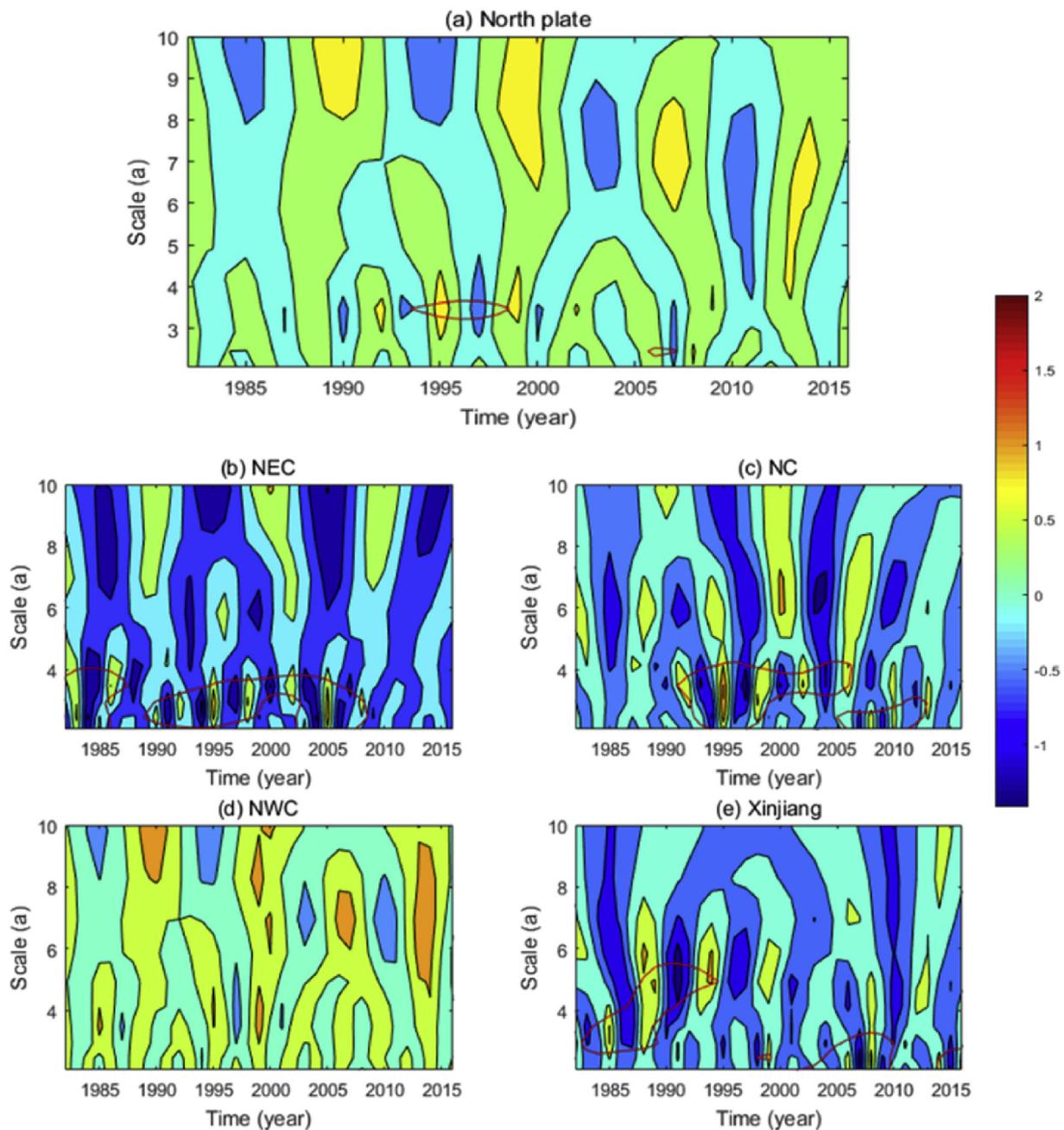
Fig. 4. Wavelet transform for the growing season mean comprehensive climate factor over the North plate(The color depth indicates the size of the wavelet coefficients; the ordinate is the time scale in years, with an interval of 5 years; and the abscissa is the time series of 1981–2015. The range enclosed by the red solid line is the 95% significance test.).

That of the South plate showed an obviously increasing trend with a variation rate of 0.25 decade^{-1}. Both passed the 95% significance test. With regard to the trend value over time, the mean CCF continued to increase over the North plate every ten years in 1981–2015. CCF increased from -0.648 in the 1980s to 0.736 in the mid-2010s, with a net increase of 1.384 (Fig. 3(a)). The CCF increased from -0.409 in the 1980s to 0.256 in the 2000s over the South plate but then fell to 0.142 (Fig. 3(b)).

In spatial terms, there were large regional differences among the CCF variations in the North plate. The maximum value of the CCF was located in NWC, and the minimum value was located in NEC. The range was 0.59 decade^{-1}. The CCF growth rate in several areas of the South plate was between 0.3 and 0.4 per decade. The minimum value of the CCF was located in NEC, at only -0.09. The maximum value of the CCF was located in EC, reaching 0.73. The values showed a decreasing trend from southwest to northeast.

At the regional scale, the growth rate of the CCF over the North plate was shown to follow the order of NWC (0.5 decade^{-1}) > Xinjiang (0.32 decade^{-1}) > NC (-0.01 decade^{-1}) > NEC (-0.09 decade^{-1}). The values for NWC and Xinjiang passed the 99% significance test. The change in the CCF was thus characterized by a pattern of being larger in the west than in the east over the North plate. The possible reasons for this finding were that the mean temperature increased by 0.4 °C decade^{-1} and the precipitation increased by 3.5 mm decade^{-1} over NWC, which led to the fastest change in the CCF for the region. The growth rate of the CCF over the South plate was shown to follow the order of EC (0.73 decade^{-1}) > CC (0.37 decade^{-1}) > SWC (0.36 decade^{-1}) > SC (0.3 decade^{-1}), and all passed the 95% significance test. The possible reasons for this finding were that the mean temperature increased by 0.33 °C decade^{-1} and the precipitation increased by 17.7 mm decade^{-1} over EC, which led to the fastest change in the CCF for the region.

3.2.2. Comprehensive climate factor periodic variations

Section 3.2.1 shows the time series trends of the growing season mean CCF in China's main grain-producing areas. It was evident that the CCF fluctuated from 1981-2015 and that it was difficult to identify a
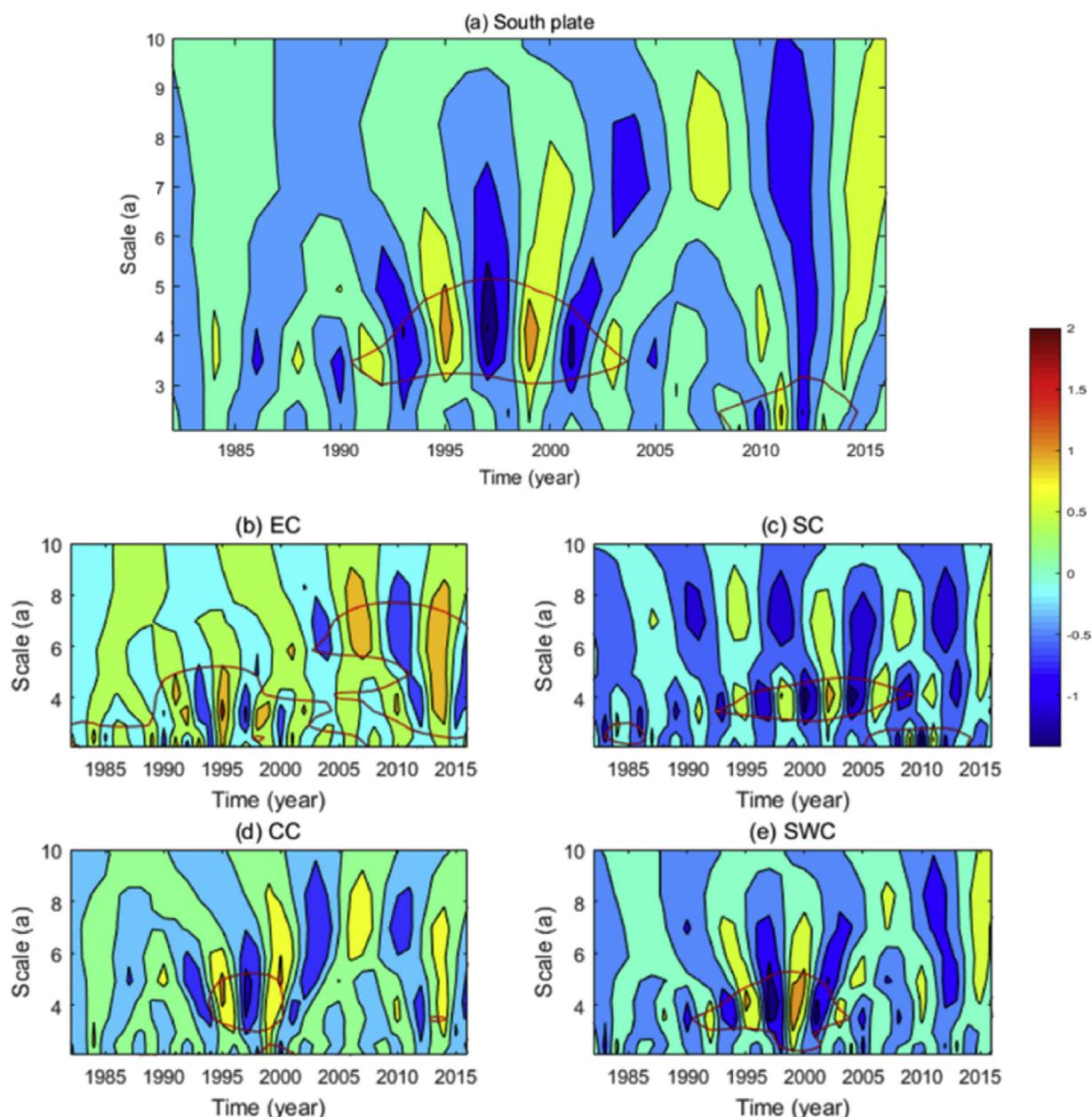
Fig. 5. Wavelet transform for the growing season mean comprehensive climate factor over the South plate.

pattern in the fluctuations The effects of the periodical variation in the CCF can thus be sufficiently observed through the wavelet analysis method.

There was no significant periodic variation over the North plate from 1981 to 2015, and there was a significant quasi-3a main periodic variation (P < 0.05) only in 1992–1999 (Fig. 4(a)). At each regional scale, there was a significant quasi-3a (P < 0.05) main periodic variation over NEC and NC (Fig. 4(b-c)). There was no significant cyclical variation over NWC or Xinjiang (Fig. 4(d-e)).

The South plate had a significant periodic quasi-4a variation (P < 0.05) in 1990–2005, and the CCF underwent a 4-year cyclical alternation process from small to large values, indicating that the South plate had a main period of quasi-4a (Fig. 5a). At each regional scale, there was a significant quasi-4a main periodic variation (P < 0.05) in 1990–2002 and 2005–2015 over EC (Fig. 5(b)). There was a significant quasi-4a main periodic variation (P < 0.05) in 1992–2010 over SC (Fig. 5(c)). There was no significant main cycle variation in CC (Fig. 5(d)). There was a significant quasi-4a main periodic variation (P < 0.05) in 1990–2005 over SWC (Fig. 5(e)).

3.3. Climate change-sensitive zones in China's grain-producing areas

To determine the responses to comprehensive climate change in different regions, we combined the variation rates of the CCF to identify climate change-sensitive zones in China's grain-producing areas.

The trend values and variation rates for the time series of climate elements could be used as the basis of climate change zoning to fully reflect the regional impacts of climate change and risk factors (Shi et al., 2014; Wu et al., 2017). In this study, the CCF is a newly constructed comprehensive indicator that measures the characteristics of climate change. Section 3.2 has shown the variations in the growing season mean CCF and analyzed the historical integrated climate characteristics in China's grain-producing areas. Based on the variation rate (0.3 decade^{-1}) of the mean CCF at the national scale, we uesd the absolute value of the CCF variation rate (indicated by the letter V) over each grain area to classify each area into three grades of climate change sensitivity: low-sensitivity ($V < 0.3$), medium-sensitivity ($0.3 \leq V < 0.4$), and high-sensitivity ($0.4 \leq V$). These regions are shown in Fig. 6.

The high-sensitivity areas were distributed in NWC and EC (Fig. 6). The low-sensitivity areas were distributed in NEC and NC. The medium-sensitivity areas were distributed in Xinjiang, SC, CC and SWC. From the
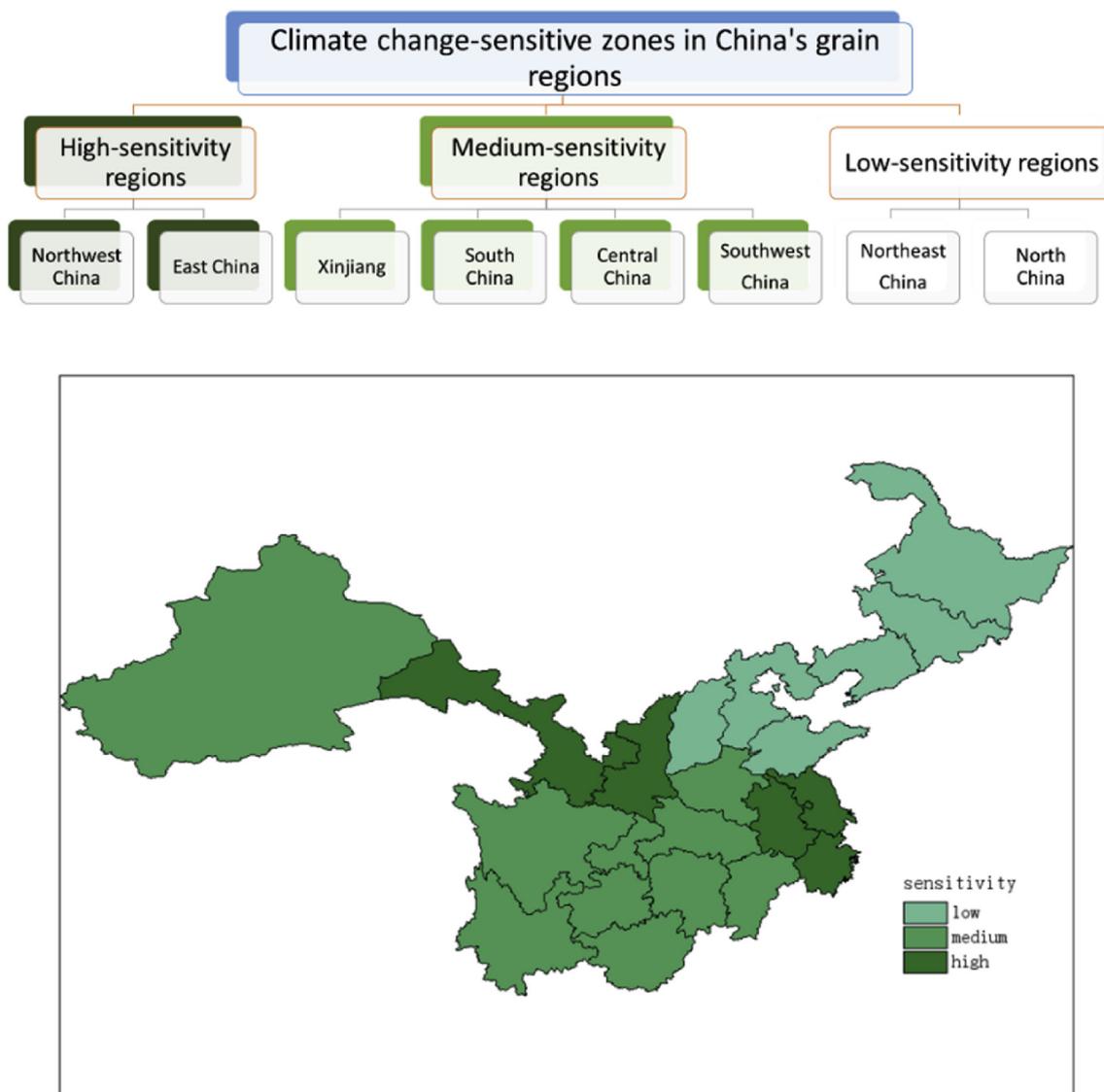
Fig. 6. China's climate change-sensitive zones in China's grain-producing areas (1981–2015 growth season) (The climate change-sensitive zones are divided by the climate tendency of Comprehensive Climate Factor, which can show the regional sensitivity to climate change.).
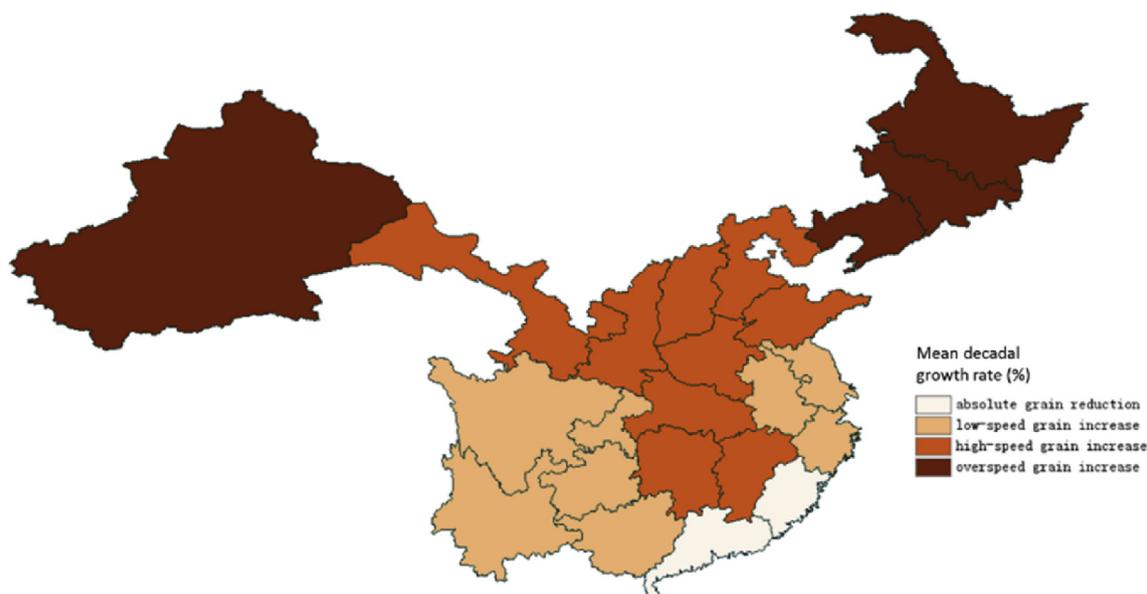
Fig. 7. The mean decadal growth rate of grain yields over China's grain-producing areas (1981–2015).

perspective of the national pattern, the climate change sensitivity of China's grain-producing areas mainly weakened from southwest to northeast. Generally, the climate change sensitivity weakened from Xinjiang to NEC in the North plate and increased from SWC to EC in the South plate.

3.4. Quantitative analysis of the impact intensity of comprehensive climate factor variations on grain yields

To explore the spatial and temporal impacts of CCF variations in China's grain-producing areas on grain yield, we used a geographical detector to quantitatively analyze CCF and grain yield based on the variations in the characteristics of actual grain yield.

We separately calculated the decadal growth rate and mean decadal growth rate of the grain yield over China's eight grain-producing areas from 1981 to 2015. Based on the mean decadal growth rate (11.2%) of the national grain yield, we divided the mean decadal growth rate (indicated by the letter P) over each grain region into four grades: absolute grain reduction ($P < 0$), low-speed grain increase ($0 \leq P < 11.2\%$), high-speed grain increase ($11.2\% \leq P < 33.6\%$), and overspeed grain increase ($P \geq 33.6\%$). We then obtained the hierarchical distribution map (Fig. 7) for the mean decadal growth rate of the grain yield over China's eight grain-producing areas over 35 years.

China's grain-producing areas mainly underwent grain increase. China's grain reduction areas were concentrated in SC (Fig. 7). The low-speed grain increase areas were distributed in EC and SWC. The high-speed grain increase areas were distributed in NC, NWC and CC. The overspeed grain increase areas were distributed in NEC and Xinjiang.

Food production is significantly affected by climate change. Exploring the impacts of climate change factors on grain yield has always been the focus of many scholars. Based on the spatial differences in grain yield discussed above, this paper attempted to use the CCF as an indicator in different periods by the geo-detector method to determine the influence intensity of the CCF on the SSH of the grain yield. Through the above discussion of the classifications of the CCF and grain yield, the corresponding values were entered into the geo-detector model for data processing, and the influence intensity value of the CCF (geographic detector q-value) was calculated. The results obtained from the geo-detector showed that the influence intensities of the CCF were 0.25 in 1991–2000, 0.23 in 2001–2010, and 0.2 in 2011–2015. The influence intensity of the CCF gradually weakened over time, indicating that the

sensitivity of the grain yield to climate change gradually decreased in each decade. This might be due to the rapid development of China's agricultural mechanization, the strengthening of agricultural ecological engineering construction, and the increased investment in agricultural subsidy policies, which have strengthened the ability of food crops to address and adapt to climate change and improved China's capacity for disaster prevention and mitigation.

4. Discussion

The CCF is an important evaluation indicator that integrates information from three climatic factors (temperature, precipitation and sunshine hours) and provides a new perspective for research on regional responses to integrated climate change. There is great application potential for the CCF. To further develop and improve the CCF indicator, more natural factors (e.g., extreme temperature, extreme precipitation, typhoons, sea level rise) can be considered in the calculation process. Baettig et al. (2007) constructed a climate change index. The index takes into account changes in extreme temperature events and extreme precipitation events, and it measures the natural variability of future climate change. At the same time, the identification of climate change-sensitive zones is an important measure for use in agriculture for addressing and adapting to climate change, and other factors affecting grain production (e.g., grain planting area, fertilizer, rural labor) can be considered as the zoning criteria. In future work, the CCF should be introduced into impact assessments that use the economic-climate model (the C-D-C model) to further reduce the uncertainty of the impact of climate change on grain production.

According to the research and analysis in this paper, the impact intensity of CCF variations on grain yield has gradually weakened in each decade, indicating that the ability to address and adapt to climate change has been enhanced in China's grain-producing areas. In fact, food production is affected by many factors, such as nature, economy and society. Among these factors, agricultural policies and government decisions play a leading role in China's agricultural production. For example, in 1995, China began to implement a responsibility system for food governors that required them to take responsibility for the balance of food resources in the region. In 1998, China began to actively promote the strategic adjustment of agricultural and rural economic structures. In 2006, China exempted agriculture from taxes and other regulatory policies. Increasing grain production has been an important policy focus (nullK). Liu et al.

(2009) found that the per capita arable land area, grain planting area and other conditions were important factors affecting grain production, and the dependence of grain yield on cultivated land resources was increasing. Yang and Lu (2010) used a spatial econometric model to analyze the factors influencing grain production in China's counties and found that technology input and production technology had positive effects on food production, while urbanization and per capita GDP had a negative impact on grain production. It can be seen that socioeconomic and climate change factors jointly affect China's grain yields. Facing the changes in the spatial and temporal patterns of comprehensive climate change in China's grain-producing areas, humans can use real-time agricultural technology, combined with meteorological monitoring and forecasting techniques to monitor the real-time dynamics of climate factors such as temperature and precipitation and to prevent possible natural disasters.

With regards to the correlation between the integrated climate change characteristics and regional climate sensitivity, areas that were highly sensitive to climate change were concentrated in most grain-producing areas, and the corresponding grain concentration reached 65.87% (Fig. 1). This study suggests that China's grain production and security can be improved with agricultural science and technology and with disaster prevention and mitigation mechanisms for food production in grain-producing areas. Through advanced agricultural science and technology, grain-producing areas have combined the real-time dynamic monitoring of comprehensive climate change characteristics and of natural factors to better address and adapt to climate change and improve food production capacity.

5. Conclusion

This paper identified China's grain-producing areas and North-South plate of grain production, constructed a Comprehensive Climate Factor, analyzed the integrated characteristics of climate change and its sensitivity over China's grain-producing areas during the past 35 years, and quantitatively assessed the impact intensity of climate change on grain yield. The major conclusions are as follows:

(1) The integrated climate change characteristics of China's grain-producing areas showed that there was a basically positive trend of the CCF in 1981–2015 (the increase in the North plate is faster than that in the South plate, 0.52 decade^{-1} > 0.25 decade^{-1}), and the climatic tendency followed a decreasing pattern from southwest to northeast. The growing season mean CCF of the North plate had no significant periodic variation, while the South plate had a main period of quasi-4a. The main periods of NEC and NC were quasi-3a, and the main periods of EC, SC and SWC were quasi-4a.

(2) According to the climatic tendencies of the CCF, the climate change-sensitive zones of China's grain-producing areas were identified. The climate change sensitivity mainly showed a spatial pattern of weakening from southwest to northeast. Among the examined regions, the high-sensitivity areas were distributed in NWC and EC, and the medium-sensitivity areas were distributed in Xinjiang, SC, CC and SWC.

(3) The impacts of CCF variations on grain yield were as follows: over the decades, the impact intensity of climate change on the grain yield gradually weakened, and the sensitivity of the grain yield to climate change also gradually weakened. Spatially, the grain yield increased from southwest to northeast, and the sensitivity to climate change weakened from southwest to northeast.

(4) Combining the variations in grain yield with the climate change sensitivity of the CCF, the main areas that are sensitive to climate change impacts on China's food production were identified. SC was the medium-sensitivity area that showed an absolute grain reduction, EC was the high-sensitivity area that showed a low-speed grain increase, and SWC was the medium-sensitivity area

that showed a low-speed grain increase. This reflected that the risks to food production in grain-producing areas were relatively high.

Based on the above results, this research transitioned from the analysis of the characteristics of a singular climate factor to a CCF impact analysis based on multiple climatic factors. This not only accurately reflected the climate change characteristics of the crop regions during the growth season but also reflected the sensitivity of climate change and its impact on food production. This study provided climate change indicators to improve the accuracy and parameterization of model simulations and predictions, which could be applied to improve simulations and predictions of the fluctuation of grain production and impact assessments The climate change impact analysis and the identification of climate change-sensitive zones in China's grain-producing areas could provide scientific support for countries or localities in addressing climate change, assessing the impact of climate change on grain yield and improving risk management.

Declarations

Author contribution statement

Jieming Chou, Yuan Xu: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed materials, data, analysis tools or data; Wrote the paper.

Wenjie Dong, Tian Xian: Analyzed and interpreted the data; Contributed data, materials, analysis tools or data; Wrote the paper.

Hong Xu, Zheng Wang: Contributed data, materials, analysis tools or data; Wrote the paper.

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

Alexander, L.V., Zhang, X., Peterson, T.C., Caesar, J., Gleason, B., Tank, A., Haylock, M., Collins, D., Trewin, B., Rahimzadeh, F., Tagipour, A., Kumar, K.R., Revadekar, J., Griffiths, G., Vincent, L., Stephenson, D.B., Burn, J., Aguilar, E., Brunet, M., Taylor, M., New, M., Zhai, P., Rusticucci, M., Vazquez-Aguirre, J.L., 2006. Global observed changes in daily climate extremes of temperature and precipitation. J. Geophys. Res. Atmos. 111, 22.

Baettig, M.B., Wild, M., Imboden, D.M., 2007. A climate change index: where climate change may be most prominent in the 21st century (vol 34, art no L17711, 2007). Geophys. Res. Lett. 34, 1.

Brunetti, M., Maugeri, M., Monti, F., Nannia, T., 2006. Temperature and precipitation variability in Italy in the last two centuries from homogenised instrumental time series. Int. J. Climatol. 26, 345–381.

Cantelaube, P., Terres, J.M., Doblas-Reyes, F.J., 2004. Influence of climate variability on European agriculture - analysis of winter wheat production. Clim. Res. 27, 135–144.

Chou, J.M., Dong, W.J., Feng, G.L., 2011. The methodology of quantitative assess economic output of climate change. Chin. Sci. Bull. 56, 1333–1335.

Chou, J.M., Xu, Y., Dong, W.J., Xian, T., Wang, Z., 2019. Research on the variation characteristics of climatic elements from April to September in China's main grain-producing areas. Theor. Appl. Climatol. 137 (3–4), 3197–3207.

C.M.A., 2018. China Blue Book on Climate Change (2018) [R]. Beijing. Climate Change Center of China Meteorological Administration.

Dai, X.G., Chou, J.F., 1995. Wavelet Analysis of the Sandstorm in Gansu Province. Meteorol. Mon. 21, 10–15.

Gallegati, M., 2018. A systematic wavelet-based exploratory analysis of climatic variables. Clim. Change 148, 325–338.

Giorgi, F., 2006. Climate change hot-spots. Geophys. Res. Lett. 33, 4.

Holst, R., Yu, X.H., Gruen, C., 2013. Climate change, risk and grain yields in China. J. Integr. Agri. 12, 1279–1291.

Huang, J.Y., 2004. Meteorological Statistical Analysis and Forecasting Method, third ed. Meteorological Press.

Hui, J.U., Wei, X., YinLong, X.U., ErDa, L.I.N., 2005. Impacts of climate change on wheat yield in China. Acta Agronomica Sinica 31, 1340–1343.

IPCC, 2014. Impacts, adaptation, and vulnerability. Part a: global and sectoral aspects. In: Field, C.B., Barros, V.R., Dokken, D.J., et al. (Eds.), Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Jung, H.S., Choi, Y., Oh, J.H., Lim, G.H., 2002. Recent trends in temperature and precipitation over South Korea. Int. J. Climatol. 22, 1327–1337.

Li, Y.C., Li, Y., Zhu, G.R., 2018. A new definition method of climate-sensitive region and its prediction. Acta Geol. Sin. 73.

Liu, Y.S., Zhai, R.X., 2009. Spatial-temporal pattern changes and optimal strategy of grain production in China since 1990s (in Chinese). Areal Res. Dev. 28, 1–5.

Liu, H., Li, X.B., Fischer, G., Sun, L.X., 2004. Study on the impacts of climate change on China's agriculture. Clim. Change 65, 125–148.

Liu, Y.S., Wang, J.Y., Guo, L.Y., 2009. The spatial-temporal changes of grain production and arable land in China. Sci. Agric. Sin. 42, 6.

Lu, W.C., Mei, Y., 2007. Empirical studies on the variation and contributing factors of regional grain production strcuture in China——based on spatial econometrics models. j. China Agric. Univ. 24, 140–152.

Niles, M.T., Lubell, M., Brown, M., 2015. How limiting factors drive agricultural adaptation to climate change. Agric. Ecosyst. Environ. 200, 178–185.

Qian, K.Z., Wang, X.S., Lv, J.J., Wan, L., 2014. The wavelet correlative analysis of climatic impacts on runoff in the source region of Yangtze River, in China. Int. J. Climatol. 34, 2019–2032.

Shi, P.J., Sun, S., Wang, M., Li, N., Wang, J.A., Jin, Y.Y., Gu, X.T., Yin, W.X., 2014. Climate change regionalization in China (1961–2010). Sci. China Earth Sci. 2294–2306.

Tang, G., Li, X., Guenther, F., Sylvia, P., 2000. Climate Change and Its Impacts on China's Agriculture. Acta Geographica Sinica 55 (5), 129–139.

Torrence, C., Webster, P.J., 1999. Interdecadal changes in the ENSO-monsoon system. J. Clim. 12, 2679–2690.

Wang, J.F., Xu, C.D., 2017. Geodetector: principle and prospective. Acta Geograph Sin. 72, 116–134.

Wang, J.F., Zhang, T.L., Fu, B.J., 2016. A measure of spatial stratified heterogeneity. Ecol. Indicat. 67, 250–256.

Wu, H., Hou, W., Qian, Z.H., Hu, J.G., 2012. The research on the sensitivity of climate change in China in recent 50 years based on composite index. Acta Phys. Sin. 61, 000562–000571.

Wu, S.H., Pan, T., Liu, Y.H., Deng, H.Y., Jiao, K.W., Lu, Q., Feng, A.Q., Yue, X.L., Yin, Y.H., Zhao, D.S., 2017. Comprehensive climate change risk regionalization of China. Acta Geol. Sin. 72, 3–17.

Xiong, W., Holman, I.P., You, L.Z., Yang, J., Wu, W.B., 2014. Impacts of observed growing-season warming trends since 1980 on crop yields in China. Reg. Environ. Chang. 14, 7–16.

Yan, J.P., Zheng, Y., 2001. A comparative study on environmental change response over the northern and the southern regions of the Qinling Mountains. Geogr. Res. 20, 576–582.

Yang, C., Lu, W.C., 2010. Research on County Regional Patterns of Food Production Based on Spatial Econometric Models, 6.

Zhang, L.W., Yan, J.P., Wang, X.P., Ma, Q., 2012. Climatic boundary variation of Qinling Mountains areas under the background of climate change. J. Arid Land 35, 572–577.