

Article

Drought Characteristics and Causes during Winter Wheat Growth Stages in North China

Chuanyang Xu , Zimeng Xu, Yao Li, Yuanyuan Luo *, Kai Wang, Linghui Guo and Chengyuan Hao

School of Surveying and Land Information Engineering, Henan Polytechnic University, Jiaozuo 454000, China; xcy@hpu.edu.cn (C.X.); 212304020057@home.hpu.edu.cn (Z.X.); liyao991117@gmail.com (Y.L.); 212304020096@home.hpu.edu.cn (K.W.); guolinghui@hpu.edu.cn (L.G.); hao@hpu.edu.cn (C.H.)

* Correspondence: yuanyuan@home.hpu.edu.cn

Abstract: Understanding potential drought characteristics under climate change is essential for reducing vulnerability and establishing adaptation strategies, especially in North China, a major grain production area. In this study, the key growth period of winter wheat was taken as the entry point. We comprehensively utilized data from meteorological stations and circulation factors and employed methods such as the modified Mann–Kendall test, run theory, wavelet analysis, and cluster analysis. We quantitatively assessed the drought conditions during the winter wheat growth stages using the Standardized Precipitation Evapotranspiration Index at a 1-month timescale (SPEI-1). We analyzed the spatiotemporal evolution characteristics of drought and explored the inherent correlation between drought and atmospheric circulation factors. Results indicate that the SPEI-1 index increased significantly during the entire growth period, the overwintering-jointing stage, and the heading-maturity stage at rates of 0.0058, 0.0044, and 0.0140 per year, respectively, showing a wetting trend. Higher drought frequency values were observed in northern Shanxi, northern Hebei, western Henan, and southern Shandong during the entire growth period, with the drought frequency of the overwintering-jointing stage approximately twice that of the emergence-tillering and heading-maturity stages. Furthermore, drought frequency values in southern Hebei and southern Henan decreased from high to low frequency during the heading-maturity stage compared to the overwintering-jointing period. The SPEI-1 is predominantly influenced by the Arctic Oscillation (AO), Atlantic Multidecadal Oscillation (AMO), Pacific Decadal Oscillation (PDO), and North Atlantic Oscillation (NAO), varying by growth stages.

Keywords: drought event characteristics; influencing factors; North China region; winter wheat growing period



Citation: Xu, C.; Xu, Z.; Li, Y.; Luo, Y.; Wang, K.; Guo, L.; Hao, C. Drought Characteristics and Causes during Winter Wheat Growth Stages in North China. *Sustainability* **2024**, *16*, 5958. <https://doi.org/10.3390/su16145958>

Academic Editors: Karam Alsafadi, Amit Kumar Srivastava and Brian Odhiambo Ayugi

Received: 23 May 2024

Revised: 27 June 2024

Accepted: 9 July 2024

Published: 12 July 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Drought and natural disasters are accompanied by global environmental problems, currently representing the most widespread, long-lasting, and significant natural disasters affecting human society and the Earth's environment [1]. The phenomenon of global warming is intensifying, leading to the continuous expansion of drought-prone areas [2]. This expansion, in turn, triggers a series of ecological imbalances, declines in agricultural production, and social and economic turmoil [3]. China ranks among the countries most affected by frequent and severe drought disasters worldwide. Between 1950 and 2022, the total area affected by drought in the country amounted to 1,423,979.99 million hectares, resulting in a loss of 1,153,562.20 million tons in grain production and affecting 686.69 million people's water supply [4]. As a traditionally agricultural country, China has been impacted by climate change, with droughts becoming increasingly severe since the 1990s. Severe and extreme droughts are now frequent, and the drought-affected area continues to increase by approximately 3.72% every 10 years [5].

Drought initially occurs due to prolonged periods of below-normal rainfall, commonly referred to as meteorological drought [6]. If below-normal rainfall persists, drought can

progress into agricultural and hydrological drought and eventually into socio-economic drought [7]. Due to the complexity of drought, quantifying it is challenging. The lack of direct drought measurement methods necessitates the use of drought indices, which are key in measuring drought severity [8]. The most commonly used drought indices by domestic and foreign scholars include the Standardized Precipitation Evapotranspiration Index (SPEI), Palmer Drought Severity Index (PDSI), and Standardized Precipitation Index (SPI). The PDSI lacks multiscale drought characteristics, and while the SPI can be used for multiscale comparisons, it only includes precipitation and not the drought conditions caused by climate warming [9]. The SPEI integrates both precipitation and temperature factors, characterizing drought through deviations from the climate water balance relative to average conditions [10]. It takes into account the sensitivity of drought to potential evapotranspiration and includes methods for assessing drought across multiple timescales, giving it strong applicability and unique advantages. Consequently, the SPEI has been widely applied in the North China region [11,12].

As a common natural disaster, the occurrence and development of drought are influenced by many factors, with atmospheric circulation being one of the most crucial. The El Niño-Southern Oscillation (ENSO) [13] significantly reflects the abnormal increase in sea surface temperature in the equatorial eastern Pacific Ocean. As an important climate driver, ENSO affects not only tropical and subtropical regions but also significantly impacts climate patterns in mid-high latitude regions through complex teleconnection mechanisms. This impact is particularly evident in the increased likelihood of drought in North China [14], revealing ENSO's profound and extensive regulatory role in the global climate system. The Pacific Decadal Oscillation (PDO) [15] is another significant trigger for climate change and contributes substantially to global climate variations [16]. The characteristics of the Arctic Oscillation (AO) [17] and the North Atlantic Oscillation (NAO) [18] during the northern hemisphere winter, and their impacts on climate change, are important indicators for evaluating climate system models. Studies have shown that climate variables such as ENSO and PDO may exacerbate the characteristics, duration, and intensity of drought [19,20]. ENSO is the most favorable interannual signal reflecting climate variability, with a strong influence on the climate of most regions worldwide [21,22]. However, research on the connection between atmospheric circulation factors and drought is relatively limited. Therefore, this study aims to explore the interaction between drought indices and the climate environment by using Wavelet Transform Coherence (WTC) to analyze the relationship between SPEI and large-scale circulation factors.

Winter wheat is an important food crop in North China, accounting for 45.70% to 63.40% of China's wheat production and often referred to as the "king of grains" [23]. The climate of North China is suitable for the growth of winter wheat, cold and dry in winter and warm and humid in spring, which is beneficial to the growth and development of wheat and promotes high yield and quality. There are abundant land resources in North China, which provide good conditions for winter wheat planting [24]. At the same time, the irrigation system in North China is developed, which can meet the water demand during the growth of winter wheat. These advantages mean the winter wheat planting in North China has higher economic and social benefits and makes an important contribution to our country's food security and agricultural development. Drought is the primary agricultural meteorological disaster threatening the stability of winter wheat production in the North China Plain [25]. It severely restricts the growth and development of wheat and poses a significant challenge to regional and national food security. Therefore, exploring the spatiotemporal evolution characteristics of drought and analyzing influencing factors in the North China region is of great significance.

2. Dataset and Methods

2.1. Study Area

The definition of the North China region varies slightly across different studies. Based on administrative divisions, this study defines North China as including six provinces and

municipalities: Beijing, Hebei, Tianjin, Shanxi, Shandong, and Henan (Figure 1). The North China region belongs to a semi-humid region, with annual precipitation between 400 and 800 mm and uneven distribution of precipitation throughout the year, mainly concentrated in the summer [26]. From the perspective of river basins, the region is located between the Yellow River, Huai River, and Hai River basins, belonging to a temperate semi-humid continental climate. Winter wheat, as one of the main food crops in North China, accounts for approximately 26.64% of the national grain output [27].

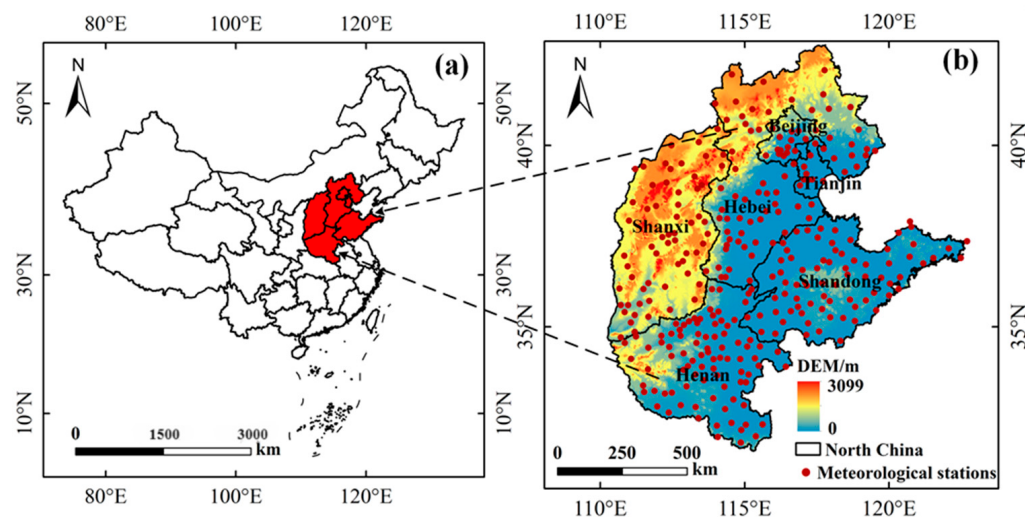


Figure 1. (a) Geographic location and (b) location of meteorological stations in the study area (DEM stands for Digital Elevation Model).

2.2. Data Sources

2.2.1. Meteorological Data

The meteorological data used in this study come from the Resource and Environmental Science Data Center of the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences (<https://www.resdc.cn/>, accessed on 10 June 2023). The dataset covers a time span from 1961 to 2021, including total monthly precipitation, minimum and maximum temperatures, wind speed, and sunshine hours, as well as geographical information such as altitude, latitude, and longitude. The data were preprocessed for strict quality control as follows. Firstly, meteorological stations with long-term missing or unrecorded values were removed. The mean replacement method was used for sporadic missing data, based on the average of the same period in adjacent months for interpolation, while for data with long-term missing values, we used the average of the same period in adjacent years for interpolation. Consequently, a total of 315 meteorological stations from 1961 to 2021 in North China were included in the analysis.

2.2.2. Climate Data

Monthly climate data were utilized during 1961–2021, including the North Atlantic Oscillation index (NAO), Pacific Decadal Oscillation index (PNA), Niño 3.4 sea surface temperature index (NIN034), Arctic Oscillation index (AO), Pacific Decadal Oscillation index (PDO), Southern Oscillation index (SOI), Trans-Niño Index (TNI), Atlantic Multi-decadal Oscillation index (AMO), and Tropical North Atlantic index (TNA). The summary of the nine indices is given in Table 1.

Table 1. Climate data used in this study with their full name, time period, and source.

Climate Factor	Name	Time Range	Data Source
NAO	North Atlantic Oscillation Index	1961–2021	https://www.cpc.ncep.noaa.gov/data/teledoc/nao.shtml , accessed on 6 July 2023
PNA	Pacific-North American Index	1961–2021	https://www.ncei.noaa.gov/access/monitoring/pna/ , accessed on 6 July 2023
NINO34	El Niño 3.4 Sea Surface Temperature Index	1961–2021	https://psl.noaa.gov/gcos_wgsp/Timeseries/Nino34/ , accessed on 6 July 2023
AO	Arctic Oscillation Index	1961–2021	https://www.ncei.noaa.gov/access/monitoring/ao/ , accessed on 6 July 2023
POD	Pacific Decadal Oscillation Index	1961–2021	https://www.ncei.noaa.gov/access/monitoring/pdo/ , accessed on 6 July 2023
SOI	Southern Oscillation Index	1961–2021	https://psl.noaa.gov/gcos_wgsp/Timeseries/SOI/ , accessed on 6 July 2023
TNI	Trans-Niño Index	1961–2021	https://psl.noaa.gov/gcos_wgsp/Timeseries/TNI/ , accessed on 6 July 2023
AMO	Atlantic Multidecadal Oscillation Index	1961–2021	https://psl.noaa.gov/gcos_wgsp/Timeseries/AMO/ , accessed on 6 July 2022
TNA	Tropical North Atlantic Index	1961–2021	https://psl.noaa.gov/data/climateindices/list/ , accessed on 6 July 2023

2.2.3. Winter Wheat Growth Stage

The growth stages of winter wheat include sowing, the seedling stage, the three-leaf stage, the tillering stage, the overwintering stage, the green-up stage, the jointing stage, the booting stage, the heading stage, the flowering stage, the grain filling stage, and the ripening stage. At different growth stages, winter wheat exhibits different sensitivities to water stress, requiring management strategies tailored to these characteristics. Referring to the research results of previous scholars [28–32] and combining the physiological characteristics of winter wheat throughout its growth period in North China, this study divides it into the stages of emergence-tillering stage (October–November), overwintering-jointing stage (December–April), and heading-maturity stage (May–June).

2.3. SPEI and Drought Event Characteristics

Due to its multiple advantages and various time scales, SPEI is suitable for monitoring and evaluating different types of droughts. SPEI is a drought index calculated based on precipitation (P) and potential evapotranspiration (PET). Various methods exist for calculating PET, with the Thornthwaite [33] and Penman–Monteith [34] methods being the most common. The Thornthwaite model, which is based on temperature estimation, may be limited in adaptability, especially in regions with large temperature differences or complex climates, where estimation results may be biased [35]. In contrast, the Penman–Monteith model considers multiple meteorological factors, resulting in more accurate estimation results [36]. Therefore, this study utilizes the Penman–Monteith method to calculate PET, with detailed definitions and calculation processes provided in the references by Vicente-Serrano et al. [37] and Yao et al. [38]. SPEI calculations were performed using the SPEI package (<https://cran.r-project.org/web/packages/SPEI/>, accessed on 15 March 2023) in R (R Core Team, Vienna, Austria).

The run theory proposed by Yevjevich (1967) [39] is one of the most commonly used methods for characterizing drought events. A run is defined as a part of a time series where all values are below or above a certain threshold. Drought events in this study were defined as the time period from months with SPEI less than -1 to months with SPEI greater than 0 . Drought events are characterized by drought frequency (DF; ratio of drought events to study years), drought duration (DD; total number of consecutive drought months), drought severity (DS; absolute value of drought events from start to end in the entire region), drought intensity (DI; ratio of DS to DD), and drought peak (DP; minimum value of SPEI during drought events). To quantify the dynamic characteristics of drought, drought events

in different growth stages of winter wheat were identified based on the run theory, and the average drought duration (MDD), average drought severity (MDS), average drought intensity (MDI), and maximum drought peak (DPmax) were calculated. The detailed computation procedure may refer to the studies of Guo et al. [40].

2.4. Trend Analysis

In order to capture the monthly drought trends and their corresponding significance, this study adopts Sen's slope and the improved non-parametric Mann–Kendall (MMK) method to assess the drought changes in North China. The non-parametric MK method is recommended by the World Meteorological Organization (WMO) for trend significance testing in climatology research [41] because of its low sensitivity to outliers, no requirements for specific sample distribution, and allowance for missing values. Therefore, Hamed and Rao [42] proposed a modified Mann–Kendall statistic to reasonably limit the influence of autocorrelation. Compared to the original MK method, MMK is more reliable and robust for capturing trends in hydro-meteorological studies [43]. Z indicates an increasing trend when positive and a decreasing trend when negative. Trend tests are conducted at specific α significance levels. When the significance levels are set at 0.01, 0.05, and 0.1, the corresponding $|Z|$ values are 2.75, 1.96, and 1.645. For specific calculation procedures, please refer to reference [44].

Sen (1968) [45] determined the size of the trend slope b , which is a stable estimate of the magnitude of monotonic trend, with the calculation formula:

$$b = \text{Median}\left(\frac{x_j - x_i}{j - i}\right) \quad i < j \quad (1)$$

2.5. Morlet Wavelet Analysis and Coherence Wavelet

Wavelet analysis is a method proposed by the geologist Morlet in the 1980s for analyzing time–frequency localization, which can clearly reflect the oscillation characteristics of various changing periods hidden in the time series of study variables, reveal the changing trends of research systems at different time scales, and qualitatively estimate the future development trends of the research objects [46,47]. This paper uses Morlet complex wavelets to study the periodical characteristics of SPEI annual averages in different growth stages in North China and calculates the wavelet variance based on the obtained wavelet coefficients. The specific calculation formula is as follows:

$$\text{Var}(a) = \int_{-\infty}^{+\infty} |W_f(a, b)|^2 db \quad (2)$$

where $\text{Var}(a)$ represents the wavelet variance, and $W_f(a, b)$ denotes the wavelet coefficients.

In order to explore the relationship between drought and atmospheric circulation factors, this study uses wavelet coherence to reveal the coupling relationship between SPEI-1 and atmospheric circulation factors [48]. The wavelet coherence spectrum is defined as follows:

$$R_n^2(n) = \frac{|S(s^{-1}W_n^{XY}(s))|^2}{S(s^{-1}|W_n^X(s)|^2) \bullet S(s^{-1}|W_n^Y(s)|^2)} \quad (3)$$

where s is the scale; S is the smoothing operator.

In addition, the correlation between SPEI and atmospheric circulation factors is quantitatively evaluated by means of the Percentage of Area Significant in Coherence (PASC) test. Therefore, the higher the PASC value, the stronger the significance of bivariate wavelet coherence.

2.6. Other Methods

To detect significant changes in the presence of mutation points or changing trends in the sequence, the Mann–Kendall mutation test method is used to detect the mutation year

of the research sequence [49]. This study adopts the inverse distance weighted interpolation method [50] to perform the spatial interpolation of drought events, visualizing the spatial pattern of drought conditions and trends in the entire study area.

3. Results

3.1. Time Variation Characteristics of Drought

3.1.1. Mutation and Trend Characteristics

During the entire growth period and the heading-maturity stage, the inflection points occurred around 1975, with the UF curve surpassing the critical values of ± 1.96 in 1984–2021, indicating significant wetting after 1984. During the emergence-tillering stage, the UF and UB curves showed multiple repeated crossings, indicating unstable variations in SPEI-1, but showed a wetting trend after 2008, though not exceeding the significance threshold. During the overwintering-jointing stage, the inflection points occurred around 1970, but the wetting trend was not significant. Significant wetting trends were observed during the entire growth period, overwintering-jointing stage, and heading-maturity stage, with growth rates of 0.0058/year, 0.0044/year, and 0.0140/year, respectively. Among them, the heading-maturity stage exhibited stage characteristics in 1961–1976 and 1977–2021, showing a significant wetting trend in 1961–1976 and a drying trend in 1977–2021 (Figure 2). At the monthly scale, SPEI-1 during the entire growth period of winter wheat showed a significant wetting trend in December, January, and June while exhibiting a non-significant drying trend in March and April (Figure 3).

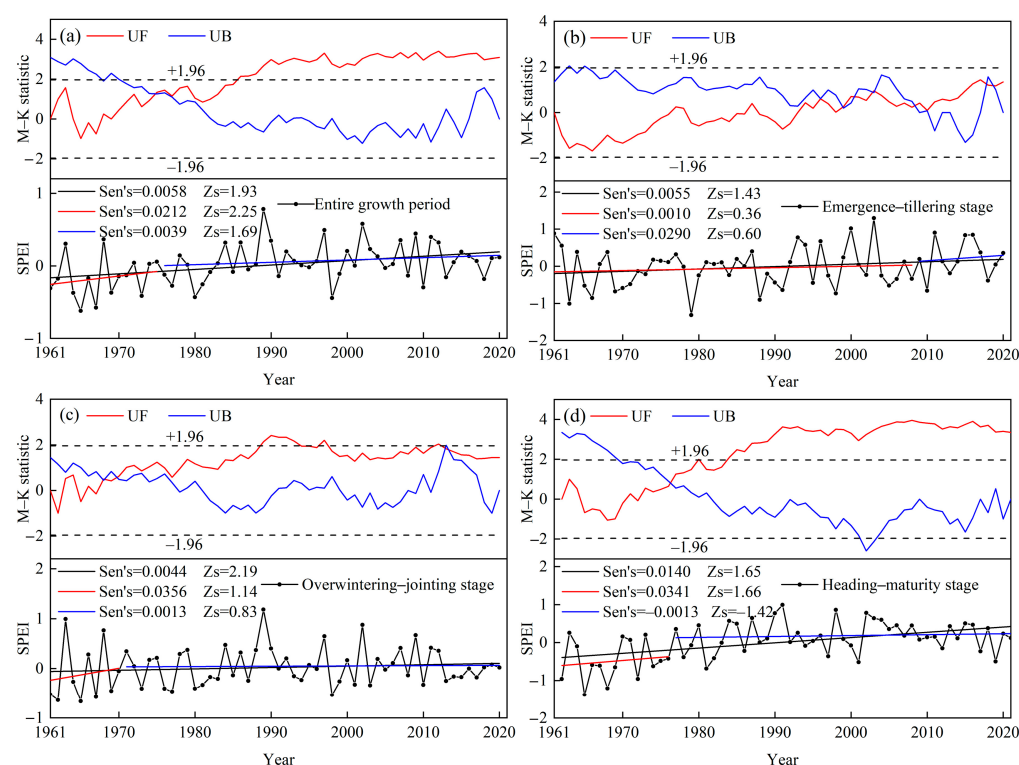


Figure 2. Detection of abrupt changes and trend variations in SPEI-1 during different growth stages of winter wheat in North China from 1961 to 2021: (a) entire growth period, (b) emergence-tillering stage, (c) overwintering-jointing stage, (d) heading-maturity stage. (Z_s represents the change in the trend of SPEI, and Sen's represents the slope of SPEI. The red line indicates the slope before the abrupt change, while the blue line indicates the slope after the abrupt change. Z_s values of 2.75, 1.96, and 1.645 correspond to significance levels of 0.01, 0.05, and 0.1, respectively).

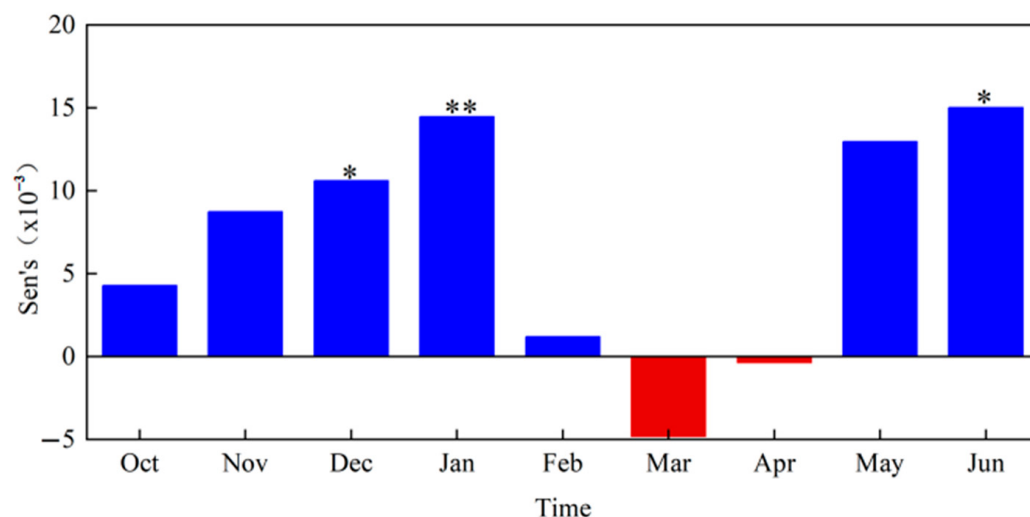


Figure 3. Slope of SPEI-1 in different months of winter wheat growth period in North China from 1961 to 2021. (The red represents drought, and the blue represents moisture; *, ** respectively indicate the different significance at 0.1, 0.05 level).

3.1.2. Periodic Characteristics

According to the real part of the wavelet coefficient contour map, there are complex multiple time scales consisting of small cycles nested within larger cycles, and the drought evolution shows two clearly different time scales of 3–7 and 12–20 years. There are three obvious cycles of wet dry alternation between 12 and 20 years, but they gradually disappear after 2010 (Figure 4a). Combining with the wavelet variance plot, it can be observed that there are two distinct peaks, corresponding to cycles of 4 years and 16 years, with the wavelet variance slightly higher for the 16-year cycle, considered as the primary cycle for the entire growth period (Figure 4b). During the emergence-tillering stage and the heading-maturity stage, there are obvious changes in the three main cycles, showing a clear pattern of alternating oscillations of drought and wetness. Combining with the wavelet variance plot, the maximum wavelet variance corresponds to the 9-year and 15-year cycles, indicating significant oscillations over these periods, thus representing the primary cycles for drought variation during these stages (Figure 4c,d,g,h). During the overwintering-jointing stage, the wavelet variance plot shows two peaks corresponding to cycles of 4 years and 19 years; however, the peak corresponding to the 19-year cycle has the highest wavelet variance and is considered the primary cycle, prevailing throughout the entire time series, exhibiting four distinct alternations between dry and wet periods (Figure 4e,f).

3.2. Spatial Pattern of Drought Situation

There were clear spatial differences in SPEI-1 variation during different growth stages of winter wheat (Figure 5). During the entire growth period, wetting trends in SPEI-1 were observed at 82.54% of the total stations, with significant wetting at 55.56% of the stations, mainly in Henan Province, Shandong Province, southern Hebei, and Tianjin City. In contrast, significant drying trends were noted in Shanxi Province (Figure 5a). At the emergence-tillering stage, SPEI-1 increased significantly at 39.05% of all stations, with these increases mainly occurring in Tianjin City, Beijing City, and Henan Province (Figure 5b). During the overwintering-jointing stage, SPEI-1 showed significant wetting at 38.41% of all stations, primarily in Henan and Shandong provinces, whereas significant drying was also noted at 29.21% of the stations, mainly in Shanxi Province (Figure 5c). Compared to other growth stages, the heading-maturity stage showed a notable increase in the number of sites with a wetting trend. Among them, 65.40% of the sites exhibited a significant wetting trend in SPEI-1, especially in Henan and Shandong provinces (Figure 5d).

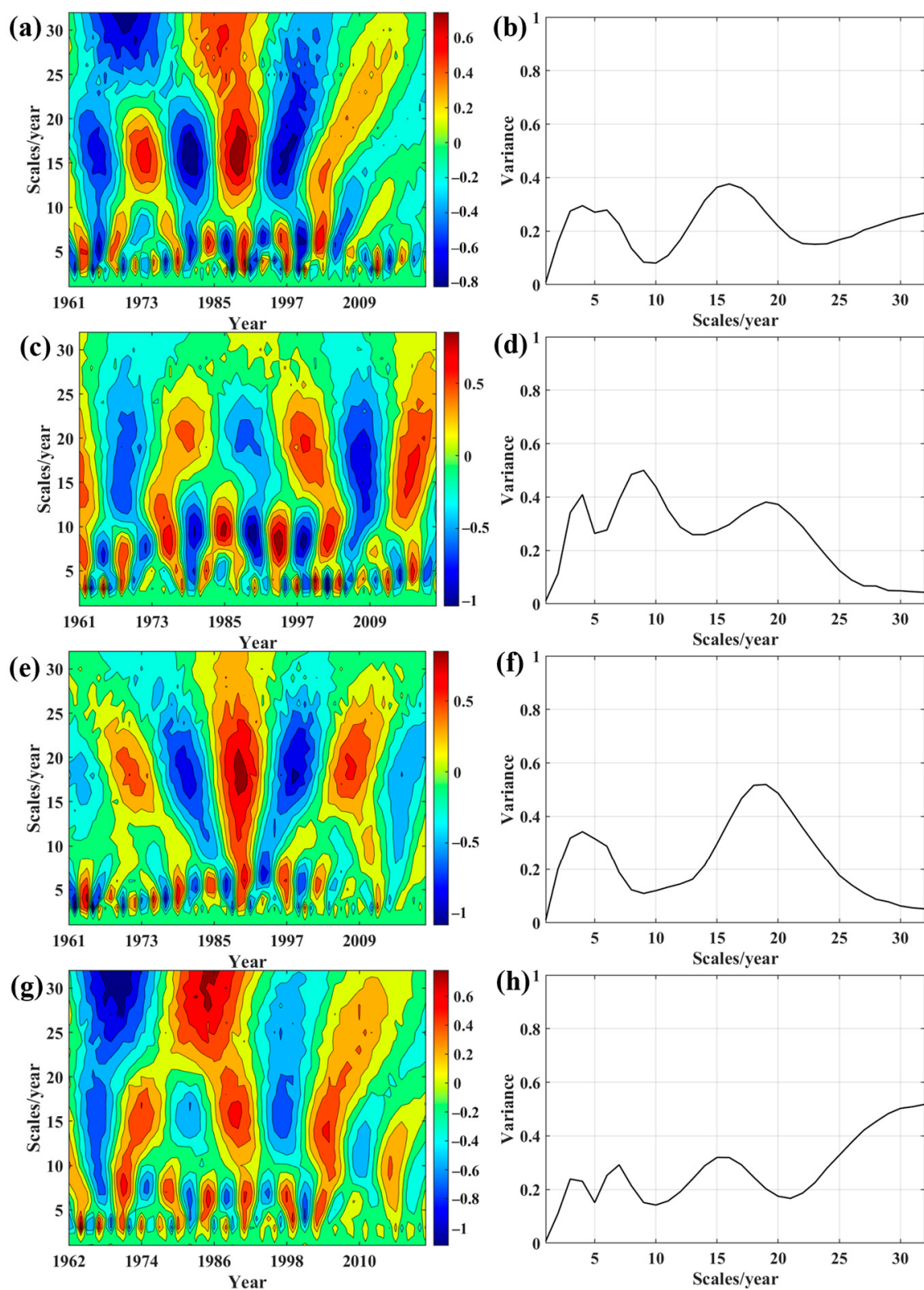


Figure 4. Map of annual average SPEI-1 Morlet wavelet coefficients and wavelet variance during (a,b) entire growth period, (c,d) emergence-tillering stage, (e,f) overwintering-jointing stage, and (g,h) heading-maturity stage in North China from 1961 to 2021.

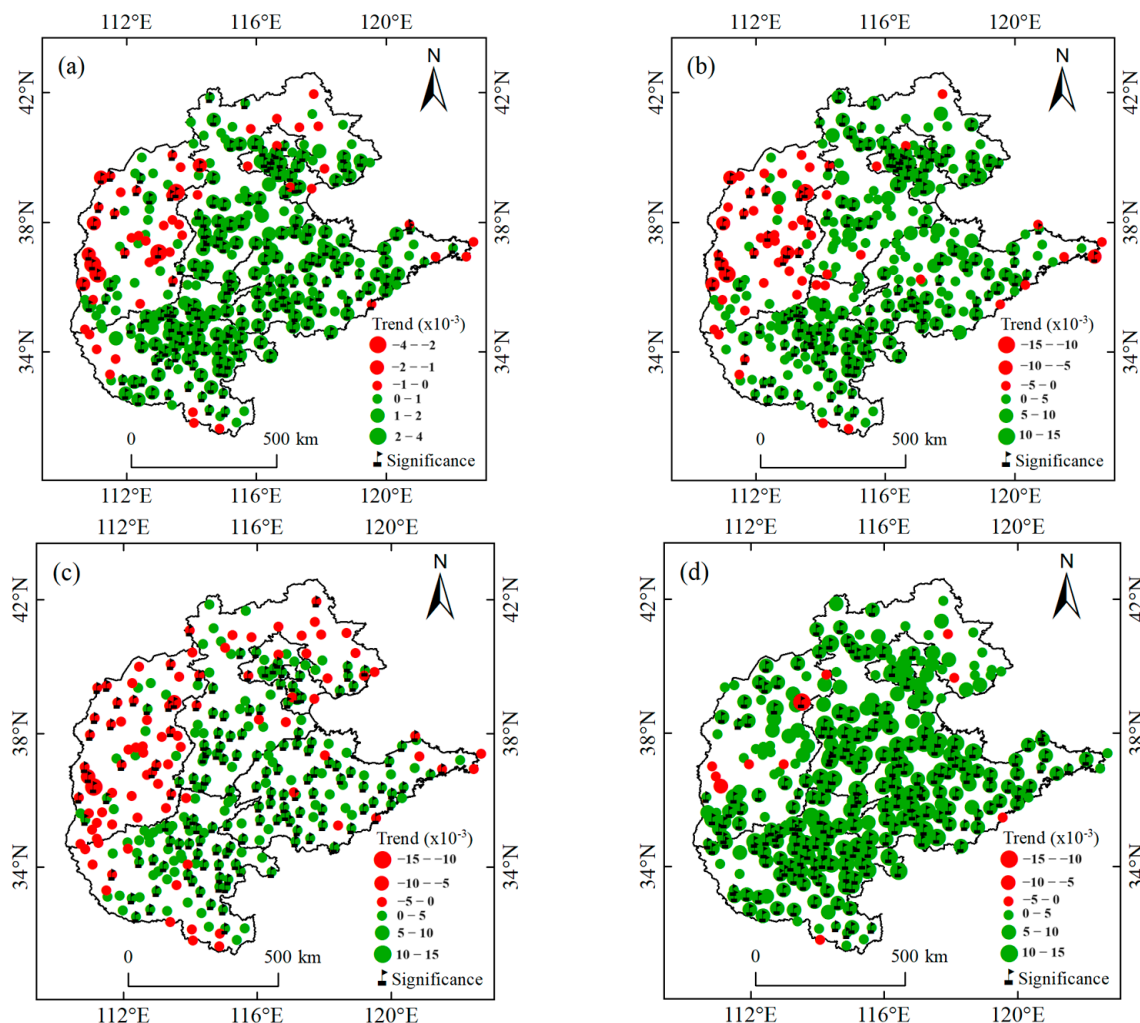


Figure 5. Spatial distribution of SPEI-1 trends in different growth stages of winter wheat in North China from 1961 to 2021: (a) entire growth period, (b) emergence-tillering stage, (c) overwintering-jointing stage, (d) heading-maturity stage.

3.3. Characteristics of Drought Events

During the entire growth period, the DF values are relatively high in northern Shanxi, northern Hebei, western Henan, and southern Shandong, but the values of MDD and MDS are relatively low. High DPmax values (>3.0) are sporadically distributed in Shanxi Province, Hebei Province, and Beijing, accounting for 9.83% of the total area [Figure 6(a1–a5)]. During the emergence-tillering stage, areas where DF values exceed 25 cover 16.64% of the total area, mainly distributed in parts of Shanxi, Henan, and Shandong. Conversely, the MDD and MDS values in these regions are relatively low. DPmax values greater than 3.0 are mainly distributed in Shanxi Province and Beijing, covering 4.49% of the total area [Figure 6(b1–b5)]. The DF values during the overwintering-jointing stage are approximately twice those during the emergence-tillering stage and heading-maturity stage. In these stages, the DF values are higher in western Henan and southern Shanxi, but the MDD and MDS values are lower [Figure 6(c1–c5)]. During the heading-maturity stage, the DF values in the southern parts of Hebei and Henan change from high frequency in the overwintering-jointing stage to low frequency. At the same time, the MDD and MDS values in these areas are relatively high (>3.0). DPmax values are mainly concentrated in the 2.0–2.5 range, covering 93.26% of the total area. In the four growth stages, MDI values are mainly concentrated in the 1.1–1.2 range, accounting for 63.83%, 62.99%, 68.66%, and 81.02% of the total area, respectively [Figure 6(d1–d5)].

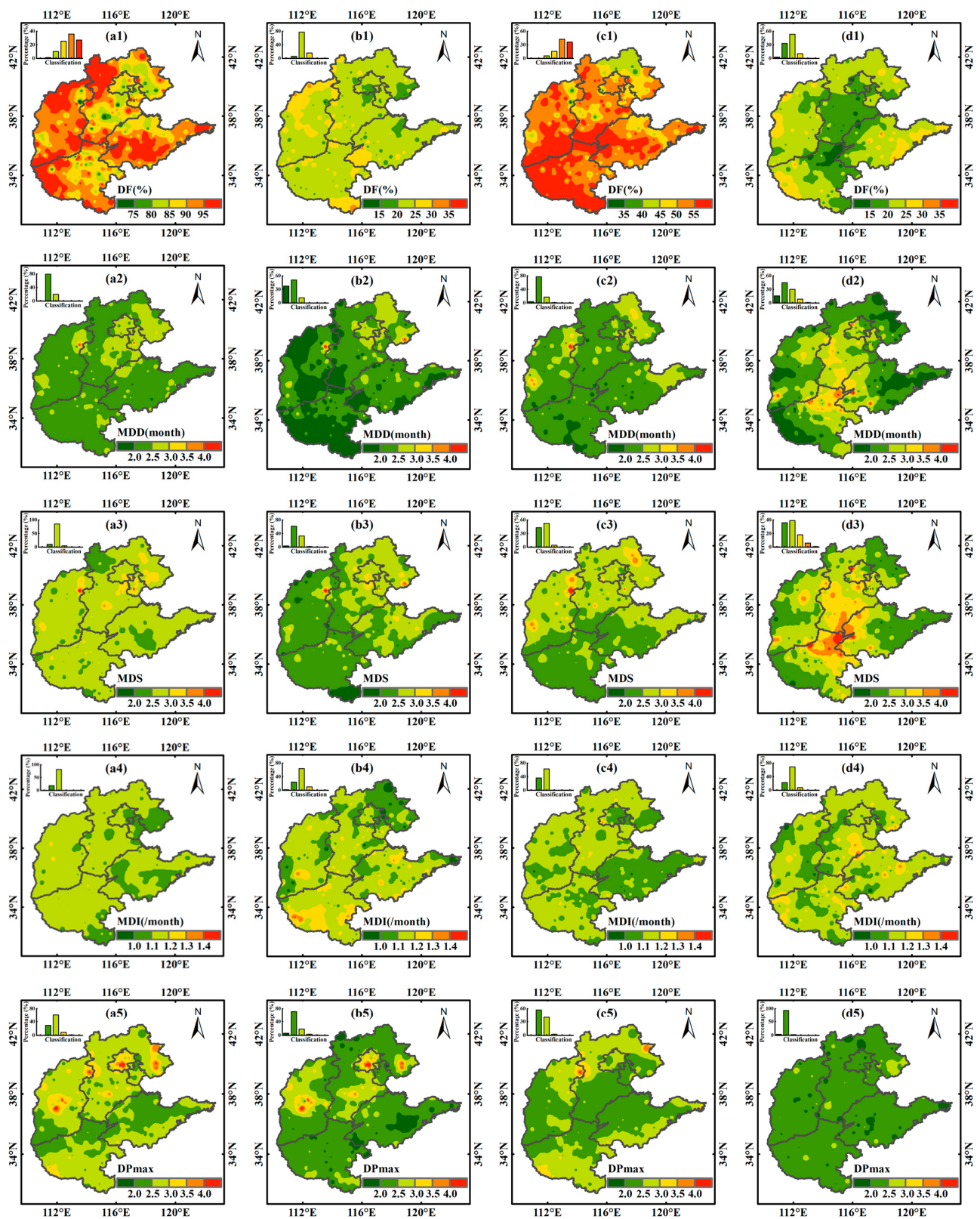


Figure 6. Spatial pattern of drought events in North China from 1961 to 2021: (a1–a5) entire growth period, (b1–b5) emergence-tillering stage, (c1–c5) overwintering-jointing stage, (d1–d5) heading-maturity stage.

To quantify the trends in drought event characteristics for different decadal periods from 1961 to 2021, Sen's slope and MMK significance test results of SPEI-1 for different growth stages of winter wheat are listed in Tables 2–5. During the entire growth period, MDI and DPmax showed significant increases in the 1960s and significant decreases in the 1990s and 2000s. The DF in the 2010s significantly decreased to -100 , indicating a significant reduction in drought events during this period (Table 2). During the emergence-tillering stage, drought event characteristics in the 2000s exhibited a significant decreasing trend, indicating a decrease in the severity and frequency of drought during this period (Table 3). During the overwintering-jointing stage, drought event characteristics were more severe in the 1960s, with significant increases in MDI and MDS. Drought characteristics remained relatively stable in the 2000s, with little change in various drought indicators. The MDD and MDS in the 2010s showed significant decreases (Table 4). During the heading-maturity stage, significant decreases in MDD and MDS were observed in the 1970s drought events, but significant increases in DF, MDS, and DPmax were observed in the 1980s. The MDS in the 2000s and 2010s both showed significant decreases, especially with DPmax in 2010 significantly decreasing to -0.90 (Table 5).

Table 2. The slope values of inter-decadal drought event characteristics of SPEI-1 during the entire growth period of winter wheat [The slope values are on a scale of 10^{-3}].

Time	Entire Growth Period				
	DF	MDD	MDS	MDI	DPmax
1960s	0 *	0.95	2.35	0.45 **	1.46 **
1970s	0	-0.20	-0.48	-0.04	-0.52
1980s	0 *	0.49	0.57	0.04	0.81 **
1990s	52.63	-0.26	-1.41 *	-0.53 *	-1.47 **
2000s	0	0.65 *	-0.13	-0.49 **	-0.45 *
2010s	-100 **	-0.68	-1.07	-0.21	-1.32 *

*, ** indicate the different significance at 0.1 and 0.05 level, respectively. The slope values are on a scale of 10^{-3} .

Table 3. The slope values of inter-decadal drought event characteristics of SPEI-1 during the emergence-tillering stage of winter wheat [The slope values are on a scale of 10^{-3}].

Time	Emergence-Tillering Stage				
	DF	MDD	MDS	MDI	DPmax
1960s	0	1.56 *	1.97	0	-0.33
1970s	0	-1.07 *	-0.17	0.77 *	0.52 *
1980s	0 *	0	0.65	0.70 *	0
1990s	40.65 *	0 *	0.22	-0.49	-1.59 **
2000s	0 **	-5.13 **	-6.32 **	-1.03 **	-1.84 **
2010s	0	0 **	-1.28 **	0.30	-0.25

*, ** indicate the different significance at 0.1 and 0.05 level, respectively. The slope values are on a scale of 10^{-3} .

Table 4. The slope values of inter-decadal drought event characteristics of SPEI-1 during the overwintering-jointing stage of winter wheat [The slope values are on a scale of 10^{-3}].

Time	Overwintering-Jointing Stage				
	DF	MDD	MDS	MDI	DPmax
1960s	0 *	0	2.82 **	0.66 **	2.14 **
1970s	0	0	0.05	-0.08	-0.22
1980s	0 **	0.55	0.16	-0.24 ***	-0.01
1990s	0 **	-1.08 *	-1.82 **	-0.19	-0.97 *
2000s	0	0	0	0	0.03
2010s	0	-1.90 *	-2.37 **	-0.37	-1.34 *

*, **, *** indicate the different significance at 0.1, 0.05 and 0.01 level, respectively. The slope values are on a scale of 10^{-3} .

Table 5. The slope values of inter-decadal drought event characteristics of SPEI-1 during the heading-maturity stage of winter wheat [The slope values are on a scale of 10^{-3}].

Time	Heading-Maturity Stage				
	DF	MDD	MDS	MDI	DPmax
1960s	0	0.88	3.56 *	0.49 *	0.92 *
1970s	0	−2.41 *	−3.40 **	−0.21	−1.06
1980s	36.10 *	0	1.61 **	0.57	2.09 **
1990s	0	0	0.81	0.011	0.76
2000s	0	0	−2.23 **	−0.42 **	−1.30 *
2010s	0 **	0*	−0.13 *	0	−0.90 **

*, ** indicate the different significance at 0.1, 0.05 and 0.01 level, respectively. The slope values are on a scale of 10^{-3} .

3.4. Links between SPEI-1 and Climate Indices

In this study, wavelet coherence is used to analyze the correlation between SPEI-1 and atmospheric circulation factors (Figure 7). The PASC values are calculated in the wavelet coherence, in order to obtain the different influential effects of atmospheric circulation factors on meteorological drought (Figure 8). During the entire growth period, SPEI-1 exhibits a significant resonance period with AO, PNA, and TNA, which follows a banded distribution along the time series, spanning approximately 110 to 192 months. This resonance period covers a long time span and displays positive phase, negative phase, and negative phase relationships, indicating strong correlations in the low-energy zone within this time domain. Additionally, SPEI-1 shows a resonance period with PDO during 1998–2010, ranging from 16 to 27 months, exhibiting a significant positive phase relationship. However, during 2014–2018 and 1961–2010, resonance periods of 8–12 months and 122–192 months, respectively, are observed, showing significant negative phase relationships. In the bivariate wavelet coherence, the PASC (15.09%) value of SPEI-1 and AO is the largest (Figure 8a).

During the emergence-tillering stage, SPEI-1 exhibits a significant resonance period with AMO from 1975 to 2007, ranging from 13 to 23 months, showing a significant negative phase relationship. Additionally, during the period from 1961 to 2021, a resonance period ranging from 32 to 48 months is observed, exhibiting a significant positive phase relationship; however, only the period from 1984 to 2000 passes the confidence test. SPEI-1 also shows multiple significant resonance periods with NINO34. During the years 1963–1966, 1994–1999, and 2007–2017, resonance periods of 2.5–4 months, 1–3.8 months, and 1–4 months, respectively, are observed, with SPEI-1 changes lagging behind NINO34 changes by 1/4 of a cycle. Additionally, during the years 1980–1990 and 1977–1988, resonance periods of 3.8–7.5 months and 8–10 months, respectively, are observed, showing a significant positive phase relationship. Furthermore, SPEI-1 exhibits resonance periods with SOI during the years 1976–1989 and 1972–1986, ranging from 4 to 6.5 months and 7.8 to 10 months, respectively, showing a significant negative phase relationship. Finally, SPEI-1 shows a significant resonance period with TNA from 1975 to 2006, ranging from 12 to 23 months, exhibiting a significant negative phase relationship. In the bivariate wavelet coherence, the PASC (21.93%) value of SPEI-1 and AMO is the largest (Figure 8b).

During the overwintering-jointing stage, SPEI-1 exhibits an extremely significant negative phase resonance period with AMO spanning the entire time domain, ranging from 82 to 96 months. SPEI-1 also shows intermittent resonance periods with NAO ranging from 1 to 8 months. Specifically, during the years 1964–1971 and 2001–2014, resonance periods of 10–16 months are observed, displaying significant positive and negative phase relationships, respectively. SPEI-1 and PDO exhibit a significant negative phase relationship with a banded resonance period distributed throughout the entire time domain at 52–96 months. Additionally, during the years 1999–2016, a resonance period of 9–16 months is observed, showing a significant positive phase relationship. Regarding PNA, resonance periods are observed during various time intervals. Specifically, during the years 1975–1978, 1987–2000, 1983–1999, and 1990–1999, resonance periods of 5.5–11 months,

26–39 months, 52–60 months, and 83–100 months, respectively, are observed, displaying significant negative phase relationships. Furthermore, during the years 1996–2003 and 2007–2018, resonance periods of 3.38–4.13 and 3.29–4.13 months, respectively, are observed, showing significant positive phase relationships. In the bivariate wavelet coherence, the PASC (21.33%) value of SPEI-1 and PDO is the largest (Figure 8c).

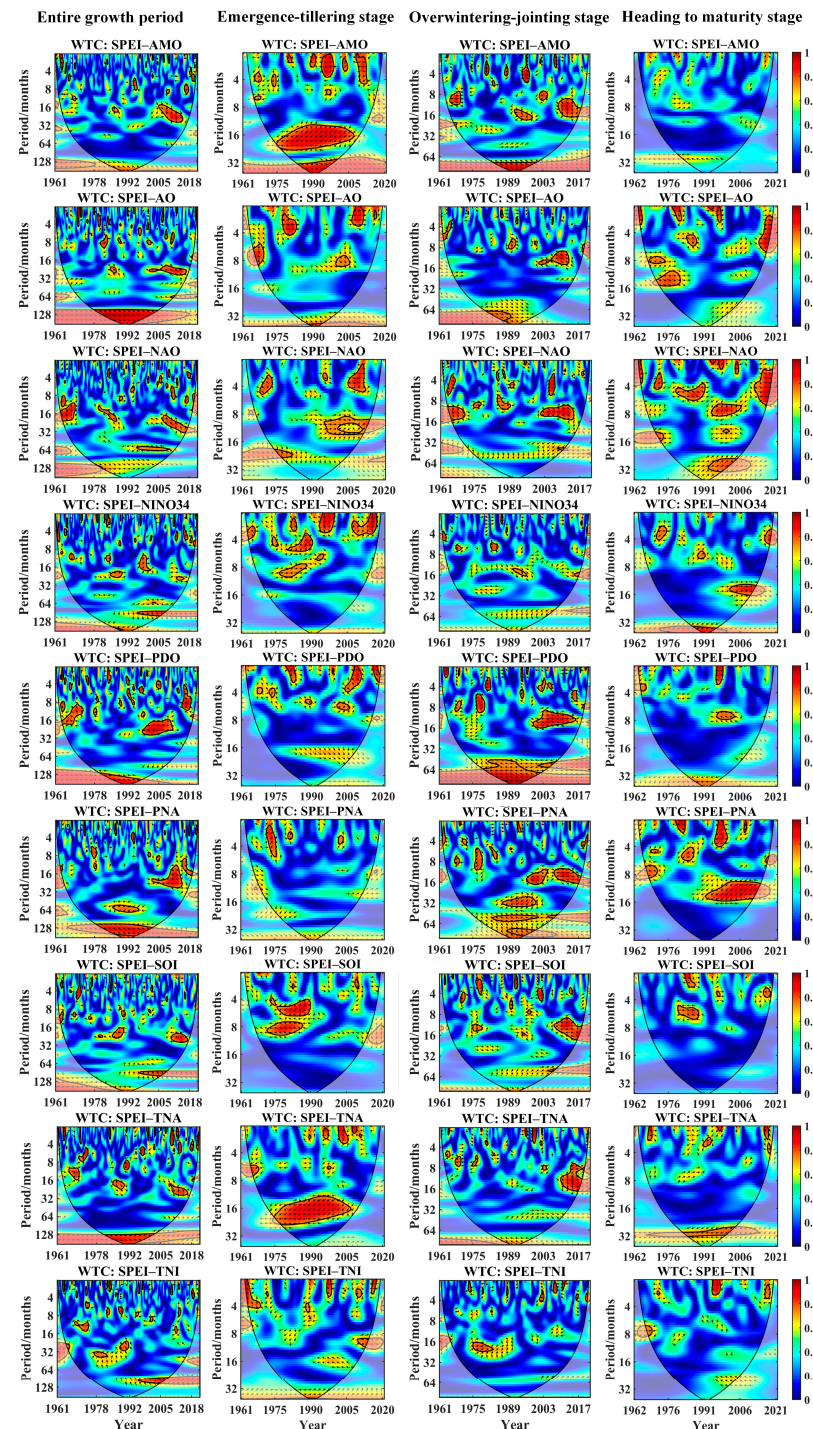


Figure 7. The wavelet coherence between climate indices and SPEI-1 in North China. The 95% confidence level against red noise is depicted as a thick contour, and the black arrows indicate the phase condition. The phase relationships between the climate indices and SPEI-1 are denoted by arrows: in-phase pointing right, anti-phase pointing left, climate indices leading SPEI-1 by 90° pointing up, and SPEI-1 leading climate indices by 90° pointing down.

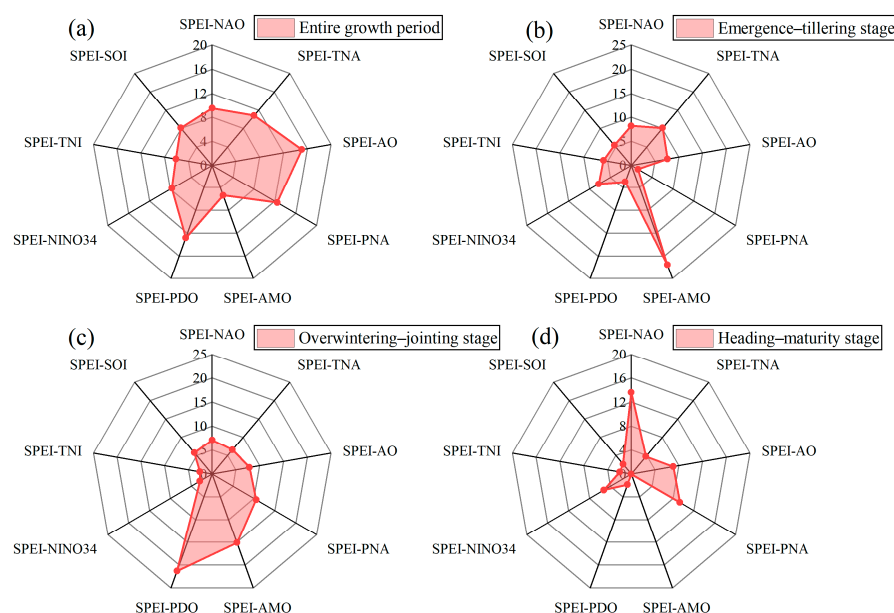


Figure 8. PASC values between SPEI-1 and climate indices: (a) entire growth period, (b) emergence–tillering stage, (c) overwintering–jointing stage, (d) heading–maturity stage. (The red dots represent the percentage of significant coherence area between SPEI and atmospheric circulation factors, determined through a 95% significance level test).

During the heading to maturity stage, SPEI-1 and AO had resonance periods of 1–3.2 months, 7.5–8 months, 1–3 months, and 2–7 months in 1964–1965, 1969–1974, 1971–1981, 1996–1998, and 2014–2019, showing a significant positive phase relationship; SPEI-1 and NAO had resonance periods of 1–4 months, 13–16 months, and 2–7 months in 1963–1965, 1970–1974, 1993–2003, and 2012–2019, showing a significant positive phase relationship; There were resonance periods of 2.5–4.5 months, 3.5–6 months, and 6.5–8 months in 1970–1973, 1979–1991, and 1994–2006, showing a significant negative phase relationship. SPEI-1 and PNA had resonance periods of 6.5–8.5 months, 4–8 months, 1–2.5 months, 1–4.5 months, and 10–16 months in 1966–1971, 1981–1987, 1979–1983, 1995–2001, and 1991–2014, showing a significant negative phase relationship. In the bivariate wavelet coherence, the PASC (13.62%) value of SPEI-1 and NAO was the largest (Figure 8d).

4. Discussion

4.1. Trends and Regional Differentiation Characteristics of Drought Changes

In this study, we found that SPEI-1 during different growth stages of winter wheat exhibited a wetting trend, with significant wetting observed during the entire growth period, the overwintering–jointing period, and the heading–maturity stage. Wu et al. [51] reported a moistening trend in the SPEI-1 during the winter wheat growth period in North China, which is consistent with our findings. In contrast, Li et al. [52] showed the drought trend during the winter wheat growth period in the North China region intensified from 1980 to 2013. The reasons for these differences may be attributed to variations in the calculation methods of potential evapotranspiration (PET). For instance, PET computed using the Thornthwaite and Penman–Monteith methods may produce contrasting outcomes in arid and semiarid regions, showing divergent trends [53]. Previous studies have indicated that the Penman–Monteith method is more suitable for application in the North China region [54]. Another possible explanation is that the number of meteorological stations can lead to differences in the spatial distributions of SPEI values between analyses [55]. Additionally, discrepancies may be influenced by how the boundaries of the North China region are defined. Spatially, the main areas showing a wetting trend during different growth stages of winter wheat in North China are located in Henan Province, Shandong

Province, southern Hebei Province, and Beijing. Conversely, the regions exhibiting a drying trend are mainly in Shanxi Province, which is consistent with Sun et al.'s [56] findings. This may be related to the influence of subtropical and westerly circulation within the province, leading to rising temperatures and reduced precipitation [57].

Based on the analysis of drought event characteristics, we found that the drought DF value during the overwintering-jointing stage is approximately twice that of the emergence-tillering stage and the heading-maturity stage. The possible reasons for this phenomenon may be that, from 1981 to 2020, the aridification trend in western parts of the North China is significantly greater than that in the eastern regions, with a particularly pronounced trend towards spring aridification [58]. The drought pattern in North China has shifted from summer and autumn droughts in the 1980s to autumn and winter droughts in the 1990s and further to winter and spring droughts in the past decade [59]. This change poses a serious challenge to the growth of winter wheat during the overwintering to jointing stages. On the other hand, the North China Plain experiences cold and dry winters and hot, rainy summers, with approximately 70% of the annual rainfall occurring between June and September [60]. In comparison, the MDD area percentage during the heading-maturity stage has increased by approximately 8.08%, and the MDS area percentage has increased by about 19.77% compared to the overwintering-jointing stage. Studies have shown that over the past 60 years, Henan and Shandong have experienced a trend of warming and drying, with gradually decreasing precipitation and continuously rising temperatures [61–63]. Therefore, it is necessary to strengthen irrigation measures during the heading-maturity stage to reduce the risk of crop water shortage.

4.2. Influence Factors of Drought and Recommendations

In the context of climate change, accurately analyzing the influencing factors of drought is crucial for formulating reasonable strategies, ensuring food security, and maintaining social stability [64]. In recent years, studies have shown that the main causes of drought in the North China region have been the decreasing precipitation at a rate of -0.71 mm/10a and the increasing temperature at a rate of 0.26 °C/10a [65]. As for atmospheric circulation factor, people are gradually recognizing the crucial role of atmospheric circulation factors in this process, as they become significant drivers of drought occurrence and evolution [66]. In particular, the AMO has a distinct impact on precipitation in many regions of the world, while also serving as a notable indicator of extreme high-temperature events specifically in northern China [67]. The results of this study conclude that the main climate factors affecting drought during the entire growth period, as well as specific stages (emergence-tillering, overwintering-jointing, and heading-maturity stage) of winter wheat, are AO, AMO, PDO, and NAO. Among them, AMO has the most significant impact on the drought evolution during the emergence-tillering stage, reaching 21.93%. Studies by Dong Manyu and others have also found that AMO is a major atmospheric circulation factor affecting the onset, end, and ≥ 10 °C accumulated temperature changes within the growing season in North China [68]. In this study, a coherence wavelet analysis was performed on the basis of nine atmospheric circulation factors in order to determine the most important factors for meteorological drought. However, the complex interactions between the atmospheric circulation factors and drought are still unclear and need to be further investigated in the future.

The causes of aridification in North China are highly complex. One of the main reasons for the exacerbation of drought is the increase in evapotranspiration induced by rising temperatures. In addition to the impacts of climate change, variations in precipitation and human activities are also significant factors contributing to the severity of drought [58]. It remains to be further studied which of these factors plays a dominant role. This study uses the coherent wavelet method to reveal the coupling relationship between the SPEI and atmospheric circulation factors on a monthly time scale. Due to SPEI's sensitivity to short-term changes, the analysis results may be influenced by various random factors. Conversely, many underlying surface factors, such as topography, have a significant impact on drought.

Therefore, future research can comprehensively consider multiple factors, including climate change, precipitation variations, human activities, and underlying surface conditions, to systematically analyze the mechanisms of drought formation and determine the dominant factors and their interactions. At the same time, zonal studies should be conducted for regions with different topographies and land use types to reveal the drought characteristics and causes in each area, thereby formulating more targeted drought mitigation measures.

4.3. The Limitations of Our Study

This study analyzed the spatial and temporal evolution of drought during different growth stages of winter wheat in the North China Plain, aiming to explore the impact of drought on agriculture and provide a scientific basis for future agricultural production. The growth stages were divided based on previous studies, which may not capture the subtle differences in the impact of climate change on drought within each sub-stage. For example, the overwintering and jointing stages may exhibit different drought characteristics due to changes in temperature and precipitation but were combined in our study. Additionally, regional-scale studies are often affected by various uncontrolled factors, such as topography, soil characteristics, and local meteorological events, which may influence our analysis results. We used the 1-month scale SPEI to analyze drought evolution, as it can finely capture the impact of short-term meteorological changes on drought conditions, but it does not consider seasonal drought. Future research should consider using longer time-scale SPEI or other drought indices that account for seasonal variations to comprehensively assess the response and impact of drought at different growth stages.

5. Conclusions

This study primarily examined the spatial and temporal evolution characteristics of short-scale droughts and its influencing factors in the North China region from 1961 to 2021. The SPEI-1 for winter wheat in North China showed significant wetting trends during the entire growth period, the overwintering-jointing stage, and the heading-maturity stage, with growth rates of 0.0058/year, 0.0044/year, and 0.0140/year, respectively. The heading-maturity stage exhibited distinct phase characteristics between 1961–1976 and 1977–2021, with a significant wetting trend in the former period (1961–1976) and a drying trend in the latter period (1977–2021). Spatially, during the entire growth period, 55.56% of the stations showed a wetting trend in SPEI-1, primarily distributed in Henan Province, Shandong Province, and Tianjin City. For the emergence-tillering stage, overwintering-jointing stage, and heading-maturity stage, the stations with a significant wetting trend in SPEI-1 accounted for 39.05%, 38.41%, and 65.40% of the total stations, respectively. During the entire growth period, regions such as northern Shanxi, northern Hebei, western Henan, and southern Shandong experienced higher drought frequency, but these regions had relatively lower drought duration and severity. The overwintering-jointing stage had particularly high drought frequency, approximately twice that of the emergence-tillering stage and the heading-maturity stage. In the heading-maturity stage, the low drought duration and severity in southern Hebei and southern Henan gradually shifted to higher drought duration and severity. Across different growth stages, MDI values were mainly concentrated in the 1.1–1.2 range. The impact of atmospheric circulation factors on SPEI-1 varies across different growth stages. The primary influencing factors for SPEI-1 during the entire growth period, emergence-tillering stage, overwintering-jointing stage, and heading-maturity stage are AO, AMO, PDO, and NAO, respectively.

Author Contributions: Conceptualization, Y.L. (Yuanyuan Luo) and L.G.; methodology, C.X. and Z.X.; validation, C.X., Z.X. and Y.L. (Yao Li); data curation, K.W. and Y.L. (Yuanyuan Luo); writing—original draft preparation, C.X., Y.L. (Yuanyuan Luo) and L.G.; writing—review and editing, C.H. and Y.L. (Yao Li) All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Qinghai Kunlun High-end Talents Project, National Natural Science Foundation of China (No. 42271124), the Project of Science and Technology of the Henan Province (No. 212102310028), Young Backbone Teachers of Henan Polytechnic University, China (No. 2020XQG-02), and Surveying and Mapping Science and Technology “double first-class” Construction Project (No. GCCYJ202431).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Acknowledgments: The authors would like to thank the researchers who provided the open-source algorithms, which were extremely helpful to the research conducted in this paper.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Zhang, Q.; Han, L.Y.; Zhang, L.Y.; Wang, J.S. Analysis on the Character and Management Strategies of Drought and Drought Disaster Risk under the Climate Warming. *Adv. Earth Sci.* **2014**, *29*, 80–91. [\[CrossRef\]](#)
2. Chen, Y.N.; Li, Y.P.; Li, Z.; Liu, Y.C.; Huang, W.J.; Liu, X.G.; Feng, M.Q. Analysis of the Impact of Global Climate Change on Dryland Areas. *Adv. Earth Sci.* **2022**, *37*, 111–119. [\[CrossRef\]](#)
3. Cook, B.I.; Mankin, J.S.; Anchukaitis, K.J. Climate Change and Drought: From Past to Future. *Curr. Clim. Change Rep.* **2018**, *4*, 164–179. [\[CrossRef\]](#)
4. China Flood and Drought Disaster Prevention Bulletin Editorial Committee. Summary of the China Flood and Drought Disaster Prevention Bulletin 2020. *China Flood Drought Def.* **2020**, *31*, 26–32. [\[CrossRef\]](#)
5. Yu, M.; Li, Q.; Hayes, M.J.; Svoboda, M.D.; Heim, R.R. Are droughts becoming more frequent or severe in China based on the standardized precipitation evapotranspiration index: 1951–2010? *Int. J. Climatol.* **2014**, *34*, 545–558. [\[CrossRef\]](#)
6. Wilhite, D.A.; Glantz, M.H. Understanding: The Drought Phenomenon: The Role of Definitions. *Water Int.* **1985**, *10*, 111–120. [\[CrossRef\]](#)
7. Byakatonda, J.; Parida, B.; Moalafhi, D.B.; Kenabatho, P.K. Analysis of long term drought severity characteristics and trends across semiarid Botswana using two drought indices. *Atmos. Res.* **2018**, *213*, 492–508. [\[CrossRef\]](#)
8. Guan, J.; Liang, C.; Zhao, L.; Cui, N.B.; Wang, C.Y. Analysis of Applicability of Three Drought Indices in the Arid Area of Central Ningxia. *Res. Soil Water Conserv.* **2018**, *25*, 122–127. [\[CrossRef\]](#)
9. Yao, N.; Li, Y.; Lei, T.J.; Peng, L.L. Drought Evolution, Severity and Trends in Mainland China over 1961–2013. *Sci. Total Environ.* **2018**, *616*, 73–89. [\[CrossRef\]](#)
10. Beguería, S.; Vicente-Serrano, S.M.; Reig, F.; Latorre, B. Standardized precipitation evapotranspiration index (SPEI) revisited: Parameter fitting, evapotranspiration models, tools, datasets and drought monitoring. *Int. J. Climatol.* **2014**, *34*, 3001–3023. [\[CrossRef\]](#)
11. Dikshit, A.; Pradhan, B.; Huete, A. An improved SPEI drought forecasting approach using the long short-term memory neural network. *J. Environ. Manag.* **2021**, *283*, 111979. [\[CrossRef\]](#) [\[PubMed\]](#)
12. Liu, K.; Jiang, D.P. Analysis of Dryness/Wetness over China using Standardized Precipitation Evapotranspiration Index Based on Two Evapotranspiration Algorithms. *Chin. J. Atmos. Sci.* **2015**, *39*, 23–36. [\[CrossRef\]](#)
13. Rasmusson, E.M.; Wallace, J.M. Meteorological Aspects of the El Niño/Southern Oscillation. *Science* **1983**, *222*, 1195–1202. [\[CrossRef\]](#) [\[PubMed\]](#)
14. Wang, S.; Huang, J.; He, Y.; Guan, Y. Combined Effects of the Pacific Decadal Oscillation and El Niño-Southern Oscillation on Global Land Dry–Wet Changes. *Sci. Rep.* **2014**, *4*, 6651. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Mantua, N.J.; Hare, S.R. The Pacific Decadal Oscillation. *J. Oceanogr.* **2002**, *58*, 35–44. [\[CrossRef\]](#)
16. Mantua, N.J.; Hare, S.R.; Zhang, Y.; Wallace, J.M.; Francis, R.C. A Pacific Interdecadal Climate Oscillation with Impacts on Salmon Production. *Bull. Am. Meteorol. Soc.* **1997**, *78*, 1069–1080. [\[CrossRef\]](#)
17. Thompson, D.W.J.; Wallace, J.M. The Arctic oscillation signature in the wintertime geopotential height and temperature fields. *Geophys. Res. Lett.* **1998**, *25*, 1297–1300. [\[CrossRef\]](#)
18. Hurrell, J.W.; van Loon, H. Decadal variations in climate associated with the North Atlantic Oscillation. *Clim. Chang.* **1997**, *36*, 301–326. [\[CrossRef\]](#)
19. Martins, V.S.; Novo, E.M.; Lyapustin, A.; Aragão, L.E.; Freitas, S.R.; Barbosa, C.C.F. Seasonal and interannual assessment of cloud cover and atmospheric constituents across the Amazon (2000–2015): Insights for remote sensing and climate analysis. *ISPRS J. Photogramm. Remote Sens.* **2018**, *145*, 309–327. [\[CrossRef\]](#)
20. Nieves, A.; Contreras, J.; Pacheco, J.; Urgilés, J.; García, F.; Avilés, A. Assessment of Drought Time-Frequency Relationships with Local Atmospheric-Land Conditions and Large-Scale Climatic Factors in a Tropical Andean Basin. *Remote Sens. Appl. Soc. Environ.* **2022**, *26*, 100760. [\[CrossRef\]](#)

21. Ward, P.J.; Jongman, B.; Kumm, M.; Dettinger, M.D.; Sperna Weiland, F.C.; Winsemius, H.C. Strong influence of El Niño Southern Oscillation on flood risk around the world. *Proc. Natl. Acad. Sci. USA* **2014**, *111*, 15659–15664. [\[CrossRef\]](#) [\[PubMed\]](#)
22. Ward, P.J.; Eisner, S.; Flörke, M.; Dettinger, M.D.; Kumm, M. Annual flood sensitivities to El Niño–Southern Oscillation at the global scale. *Hydrol. Earth Syst. Sci.* **2014**, *18*, 47–66. [\[CrossRef\]](#)
23. Zhou, L.T.; Sun, S.; Guo, E.J.; Zhang, Z.T.; Zhang, F.L.; Shi, Y.Y.; Ma, H.Y.; Yang, X.G. An APSIM modified model under drought conditions and simulation winter wheat yield in North China. *J. Agric. Eng.* **2023**, *39*, 92–102. [\[CrossRef\]](#)
24. Hu, W.; Yan, C.R.; Li, Y.C.; Li, Q. Impacts of climate change on winter wheat growing period and irrigation water requirements in the north China plain. *Acta Ecol. Sin.* **2014**, *34*, 2367–2377. [\[CrossRef\]](#)
25. Zhang, Z.; Wang, P.; Chen, Y.; Zhang, S.; Tao, F.; Liu, X. Spatial pattern and decadal change of agro-meteorological disasters in the main wheat production area of China during 1991–2009. *J. Geogr. Sci.* **2014**, *24*, 387–396. [\[CrossRef\]](#)
26. Yang, S.Y.; Meng, D.; Li, X.J.; Wu, X.L. Multi-scale responses of vegetation changes relative to the SPEI meteorological drought index in North China in 2001–2014. *Acta Ecol. Sin.* **2018**, *38*, 1028–1039. [\[CrossRef\]](#)
27. Hong, S.; Hao, J.; Zhou, N.; Chen, L.; Lv, Z. Change of cultivated land and its impact on grain production pattern in Huang-Huai-Hai Plain. *Trans. China Soc. Agric. Eng.* **2014**, *30*, 268–277. [\[CrossRef\]](#)
28. Zhong, R.; Ren, Y.K.; Wang, P.R.; Lin, W.; Ren, A.X.; Sun, M.; Gao, Z.Q.; Xu, J.M. Climate Change Characteristics during the Growth Period of Winter Wheat and Its Impact on Yield in Southern Shanxi Region. *Chin. J. Ecol.* **2022**, *41*, 81. [\[CrossRef\]](#)
29. Yue, H.; Li, C.Q.; Jiang, Y.L. Analysis of Abnormal Climate Impact on the Growth and Development of Winter Wheat in Hebei During 2009–2011. *Chin. Agric. Sci. Bull.* **2012**, *28*, 306–310. [\[CrossRef\]](#)
30. Tan, Y.J.; Yang, H.J.; Li, H. Impacts of Climate Change on Winter Wheat Growth Stages in Henan Province from 1981 to 2019. *Shandong Agric. Sci.* **2020**, *52*, 30–38. [\[CrossRef\]](#)
31. Zhang, C.J.; Wang, S.; Song, Y.L.; Cai, W.Y. Research of Drought Risk Assessment for Winter Wheat in Northern China. *Arid Meteorol.* **2014**, *32*, 883–893.
32. Zou, J.L.; Xu, Y. Analysis on Meteorological Conditions of Winter Wheat Growth Period in Tai'an City from 2019 to 2020. *Agric. Disaster Res.* **2020**, *10*, 84–85. [\[CrossRef\]](#)
33. Thornthwaite, C.W. An Approach toward a Rational Classification of Climate. *Geogr. Rev.* **1948**, *38*, 55–94. [\[CrossRef\]](#)
34. Stannard, D.I. Comparison of Penman-Monteith, Shuttleworth-Wallace, and Modified Priestley-Taylor Evapotranspiration Models for wildland vegetation in semiarid rangeland. *Water Resour. Res.* **1993**, *29*, 1379–1392. [\[CrossRef\]](#)
35. Wei, J.; Wang, Z.; Han, L.; Shang, J.; Zhao, B. Analysis of Spatio-Temporal Evolution Characteristics of Drought and Its Driving Factors in Yangtze River Basin Based on SPEI. *Atmosphere* **2022**, *13*, 1986. [\[CrossRef\]](#)
36. Li, X.; Ju, H.; Sarah, G.; Yan, C.; Batchelor, W.D.; Liu, Q. Spatiotemporal variation of drought characteristics in the Huang-Huai-Hai Plain, China under the climate change scenario. *J. Integr. Agric.* **2017**, *16*, 2308–2322. [\[CrossRef\]](#)
37. Vicente-Serrano, S.M.; Beguería, S.; López-Moreno, J.I. A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index. *J. Clim.* **2010**, *23*, 1696–1718. [\[CrossRef\]](#)
38. Yao, N.; Li, L.; Feng, P.Y.; Feng, H.; Liu, D.L.; Liu, Y.; Jiang, K.T.; Hu, X.T.; Li, Y. Projections of drought characteristics in China based on a standardized precipitation and evapotranspiration index and multiple GCMs. *Sci. Total Environ.* **2020**, *704*, 135245. [\[CrossRef\]](#) [\[PubMed\]](#)
39. Yevjevich, V.M. *An Objective Approach to Definitions and Investigations of Continental Hydrologic Droughts*; Hydrology Papers; Colorado State University: Fort Collins, CO, USA, 1967.
40. Guo, L.; Luo, Y.; Li, Y.; Wang, T.; Gao, J.; Zhang, H.; Wu, S. Spatiotemporal Changes and the Prediction of Drought Characteristics in a Major Grain-Producing Area of China. *Sustainability* **2023**, *15*, 15737. [\[CrossRef\]](#)
41. Barring, L. Climate—Change or variation? *Clim. Change* **1993**, *25*, 1–13. [\[CrossRef\]](#)
42. Hamed, K.H.; Rao, A.R. A Modified Mann-Kendall Trend Test for Autocorrelated Data. *J. Hydrol.* **1998**, *204*, 182–196. [\[CrossRef\]](#)
43. Daufresne, M.; Lengfellner, K.; Sommer, U. Global Warming Benefits the Small in Aquatic Ecosystems. *Proc. Natl. Acad. Sci. USA* **2009**, *106*, 12788–12793. [\[CrossRef\]](#) [\[PubMed\]](#)
44. Tabari, H.; Talaee, P.H.; Nadoushani, S.M.; Willems, P.; Marchetto, A. A Survey of Temperature and Precipitation Based Aridity Indices in Iran. *Quat. Int.* **2014**, *345*, 158–166. [\[CrossRef\]](#)
45. Sen, P.K. Estimates of the Regression Coefficient Based on Kendall's Tau. *J. Am. Stat. Assoc.* **1968**, *63*, 1379–1389. [\[CrossRef\]](#)
46. Ma, P.S.; Wang, J.Q.; Liu, L.X.; Cui, S.L. Application of Morlet Wavelet Frequency Division in Improving Seismic Data Resolution. *Geophys. Prospect. Pet.* **2007**, *46*, 283–287. [\[CrossRef\]](#)
47. Wang, Q.; Liu, X.; Wang, Z.Y.; Zhao, L.; Zhang, Q.P. Time scale selection and periodicity analysis of grassland drought monitoring index in Inner Mongolia. *Glob. Ecol. Conserv.* **2022**, *36*, e02138. [\[CrossRef\]](#)
48. Wang, F.; Lai, H.; Li, Y.; Feng, K.; Tian, Q.; Zhang, Z.; Yang, H. Terrestrial Ecological Drought Dynamics and Its Response to Atmospheric Circulation Factors in the North China Plain. *Atmos. Res.* **2023**, *294*, 106944. [\[CrossRef\]](#)
49. Wang, Z.; Li, J.; Lai, C.; Zeng, Z.; Zhong, R.; Chen, X.; Zhou, X.; Wang, M. Does drought in China show a significant decreasing trend from 1961 to 2009? *Sci. Total Environ.* **2017**, *579*, 314–324. [\[CrossRef\]](#) [\[PubMed\]](#)
50. Mekonen, A.A.; Berlie, A.B.; Ferede, M.B. Spatial and temporal drought incidence analysis in the northeastern highlands of Ethiopia. *Geoenviron. Disasters* **2020**, *7*, 49–60. [\[CrossRef\]](#)
51. Wu, J.; Cheng, G.; Wang, N.; Shen, H.; Ma, X. Spatiotemporal Patterns of Multiscale Drought and Its Impact on Winter Wheat Yield over North China Plain. *Agronomy* **2022**, *12*, 1209. [\[CrossRef\]](#)

52. Li, Q.; Liu, Y.; Luo, L.; Wang, Y.; Wang, Q.; Ma, M. Spatiotemporal Drought Characteristics during Growing Seasons of Winter Wheat and Summer Maize in the North China Plain. *Front. Earth Sci.* **2024**, *11*, 1358987. [\[CrossRef\]](#)
53. Wang, H.; Cao, L.; Li, X.; Feng, R.; Zheng, P. Differences in drought evolution as portrayed for China using various evapotranspiration models and drought indices. *Int. J. Climatol.* **2022**, *42*, 9404–9429. [\[CrossRef\]](#)
54. Ming, B.; Guo, Y.; Tao, H.; Liu, G.; Li, S.; Wang, P. SPEIPM-based research on drought impact on maize yield in North China Plain. *J. Integr. Agric.* **2015**, *14*, 660–669. [\[CrossRef\]](#)
55. Feng, W.; Lu, H.; Yao, T.; Yu, Q. Drought Characteristics and Its Elevation Dependence in the Qinghai–Tibet Plateau during the Last Half-Century. *Sci. Rep.* **2020**, *10*, 14323. [\[CrossRef\]](#) [\[PubMed\]](#)
56. Sun, J.; Bi, S.; Bashir, B.; Ge, Z.; Wu, K.; Alsalman, A.; Ayugi, B.O.; Alsafadi, K. Historical Trends and Characteristics of Meteorological Drought Based on Standardized Precipitation Index and Standardized Precipitation Evapotranspiration Index over the Past 70 Years in China (1951–2020). *Sustainability* **2023**, *15*, 10875. [\[CrossRef\]](#)
57. Li, X. Causes of Drought Disasters and Mitigation Strategies in Shanxi. *Anhui Agric. Bull.* **2012**, *18*, 180–181.
58. Song, K.; Liu, J.H.; Yuan, X.S. Analysis of the Spatial and Temporal Characteristics of Drought in North China from 1981 to 2020 Based on SPEI Index. *J. Inst. Disaster Prev. Tech.* **2023**, *25*, 49–58.
59. Liu, X.; Pan, Y.; Zhu, X.; Yang, T.; Bai, J.; Sun, Z. Drought evolution and its impact on the crop yield in the North China Plain. *J. Hydrol.* **2018**, *564*, 984–996. [\[CrossRef\]](#)
60. Cui, Y.; Zhang, B.; Huang, H.; Zeng, J.; Wang, X.; Jiao, W. Spatiotemporal Characteristics of Drought in the North China Plain over the Past 58 Years. *Atmosphere* **2021**, *12*, 844. [\[CrossRef\]](#)
61. Zhang, Q.; Hui, X.Y.; Zhang, Y.J. Analysis on Temporal and Spatial Variation of Rainfall in in Shanxi Province in Recent 61 Years. *Water Resour. Hydropower Eng. Des.* **2021**, *40*, 24–26. [\[CrossRef\]](#)
62. Gu, X.H.; Feng, R.Y.; Wang, H.J.; Gao, W.; Yan, G.Y.; Guo, F. Change Trends of Temperature Variation over the 50 Years in Shanxi Province. *Shanxi Agric. Sci.* **2015**, *43*, 1160–1164. [\[CrossRef\]](#)
63. Zhang, Z.G.; Geng, Y.X.; Cai, M.T.; Zhang, X.L.; Sun, Z.X.; Yin, J.Y. Spatial-Temporal Evolution and Trend Analysis of Climate Potential Productivity in Henan Province during 1978–2017. *Res. Soil Water Conserv.* **2020**, *27*, 247–253. [\[CrossRef\]](#)
64. Kang, Y.; Khan, S.; Ma, X. Climate change impacts on crop yield, crop water productivity and food security—A review. *Prog. Nat. Sci.* **2009**, *19*, 1665–1674. [\[CrossRef\]](#)
65. Duo, A.; Zhao, W.J.; Qua, X.Y.; Jing, R.; Xiong, K. Spatio-temporal variation of vegetation coverage and its response to climate change in North China plain in the last 33 years. *Int. J. Appl. Earth Obs.* **2016**, *53*, 103–117. [\[CrossRef\]](#)
66. Forootan, E.; Khaki, M.; Schumacher, M.; Wulfmeyer, V.; Mehrnegar, N.; Dijk, A.I.J.M.V.; Brocca, L.; Farzaneh, S.; Akinluyi, F.; Ramillien, G.; et al. Understanding the global hydrological droughts of 2003–2016 and their relationships with teleconnections. *Sci. Total. Environ.* **2019**, *650*, 2587–2604. [\[CrossRef\]](#) [\[PubMed\]](#)
67. Wu, X.; Wang, L.; Yao, R.; Luo, M.; Li, X. Identifying the dominant driving factors of heat waves in the North China Plain. *Atmos. Res.* **2021**, *252*, 105458. [\[CrossRef\]](#)
68. Dong, M.Y.; Li, J.M.; Wang, L.X.; Liu, P.P.; Jiang, Y.; Wu, Z.F. Climatic Characteristics of Climatic Growing Season and Impact Factors in North China during 1960–2017. *Sci. Geogr. Sin.* **2019**, *39*, 1990–2000. [\[CrossRef\]](#)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.