Characteristics of Dry and Wet Climate in Shandong Province Based on Standardized Precipitation Index

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Abstract Based on the monthly precipitation data of 116 meteorological stations in Shandong Province during 1970 – 2021, standardized precipitation index (SPI) was calculated, and the methods of linear fitting, mutation test and Morlet wavelet analysis were used to analyze the change trend and temporal and spatial distribution characteristics of SPI index in the past 52 years. The results show that there were more normal years in Shandong Province, and the frequency reached 38.46%. There was severe drought in the 1980s and more wet years after 2003. SPI index showed an upward trend in spring, summer and winter but a weak arid trend in autumn. In addition, intense dry weather was more frequent in summer. Spatially, the climate was normal or humid in most areas of Shandong Province. The regions with more wet years were located in the central and northeast Shandong and the peninsula, while the climate was normal in the southwest and north of Shandong. The areas with more dry years were mainly located in the northwest of Shandong Province. There was mainly local and global drought in Shandong Province, and the arid area showed a decreasing trend. In the past 52 years, Shandong Province experienced quasi-4 times of alternation between dry and wet climate. The long period of 21 a was the first main period, and the climate would be still wet in Shandong Province in the future. In terms of mutation, the climate in Shandong Province became humid after 2003, and 2003 was the mutation point. After the abrupt change, the climate changed from gradually drying to wetting.

Key words Standardized precipitation index; Shandong Province; Dry and wet climate characteristics; Trend analysis **DOI** 10. 19547/j. issn2152 – 3940. 2024. 03. 002

Since the advent of industrialized society, temperature has increased more rapidly. According to the Sixth Assessment Report of IPCC, the global surface average temperature has risen by about 1°C in the past 100 years, and the global temperature is expected to rise by 1.5 °C in the future^[1]. The trend of global warming is becoming more and more severe, and extreme weather such as drought and flood occur frequently, causing increasingly serious economic, environmental and security problems. As a large agricultural province in the north of China, Shandong Province has long ranked first in agricultural added value. However, due to its special geographical location, Shandong Province is affected by not only the western Pacific subtropical high but also the Pacific ENSO event and the Indian Ocean IOD. Therefore, the climate is relatively complicated, and the spatial and temporal distribution of rainfall is not even, so that it is prone to drought and flood^[2-3]. In order to reduce the loss of drought and flood disasters and ensure the agricultural and ecological safety of Shandong Province, it is of great significance to study the characteristics and changing trends of dry and wet climate in Shandong Province under the background of climate warming.

In meteorology, the study of drought phenomenon is usually based on drought indicators. Commonly used meteorological

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drought indicators include precipitation anomaly percentage (Pa)^[4], standardized precipitation index (SPI)^[4-5], standardized precipitation evapotranspiration index (SPEI) [4,6], Palmer drought severity index (PDSI)^[7], meteorological comprehensive drought index (MCI)^[4], and precipitation Z index^[8]. The most important meteorological factor affecting the occurrence of drought and flood is precipitation, and SPI index has strong stability. Comparisons between different time scales and regions can be made, and it has been widely used and verified in drought research. For instance, based on SPI index, Afrin et al. studied the drought in the northern region of Bangladesh, and found that the frequency of moderate and severe drought in northern Bangladesh was high, and sometimes extreme drought also took place; the trend of drought may continue in the future [9]. Yu Jiarui et al. analyzed the SPI index of Heilongjiang Province, and found that the drought in summer and autumn showed an increasing trend, while the drought in spring and winter showed a decreasing trend^[10]. Using the spatial clustering method, Li Ming et al. made climate regionalization in northeast China to study the SPI index of each climate region, and found that there were basically three drought periods in different sub-regions; the late 1960s, the mid-late 1970s to the early 1980s, and the late 1990s to the 2000s, and significant periods of 3 – 8 and 11 a exist in different sub-regions^[11].

In recent years, some scholars have studied the drought and flood in Shandong Province, but most of them use the precipitation anomaly percentage index and precipitation Z index, or only for some areas in Shandong Province. For example, by comparing the

annual average precipitation anomaly percentage, Wan Mingbo *et al. found that severe drought happened in the* 1980s, and drought and flood alternated in the 1990s^[12]. Lu Guirong *et al.* compared the application of Z index and precipitation anomaly percentage in Rizhao City, and found that Z index had a better indication effect on the degree of drought and flood than precipitation anomaly percentage; from the analysis of annual variation of Z index, it was found that drought was more serious than flood disaster in Rizhao City on the whole^[13]. Besides, the drought in Shandong Province has been studied by SPI index. For example, Ma Mengmeng *et al.* found that the frequency of drought in Shandong Province during 1961 – 2017 was about 30.66%, and Shandong was divided into four regions according to drought intensity. However, the data of 23 stations were used in this study, and the representativeness of data is needed to be studied further^[14].

In this paper, based on the monthly precipitation data of 116 meteorological stations in Shandong Province from 1970 to 2021, SPI index was calculated to analyze the annual and seasonal variation of SPI index, and the frequency of dry and wet climate and the ratio of drought stations were also studied. Besides, the periodic analysis and mutability test for annual SPI index was conducted by Morlet wavelet transform and mutation test, and the tempo-

ral and spatial changes of dry and wet climate characteristics before and after the abrupt change were discussed to understand the change trends of dry and wet climate characteristics in Shandong in recent 52 years and then provide a theoretical basis for disaster prevention and reduction and agricultural security in Shandong Province.

1 Data and methods

1.1 Data sources According to the coverage degree of stations, the amount of missing data and the continuity of data, the monthly precipitation data of 116 meteorological stations (including national benchmark stations and basic stations) in Shandong Province from 1970 to 2021 was selected. The distribution of the stations is shown in Fig. 1. The data came from the Meteorological Information Center of Shandong Meteorological Bureau. The quality of the data has been checked to eliminate errors and missing records, so as to ensure the continuity and accuracy of data resources. In this study, seasons in Shandong Province were divided into spring (from March to May), summer (from June to August), autumn (from September to November), and winter (from December to February).

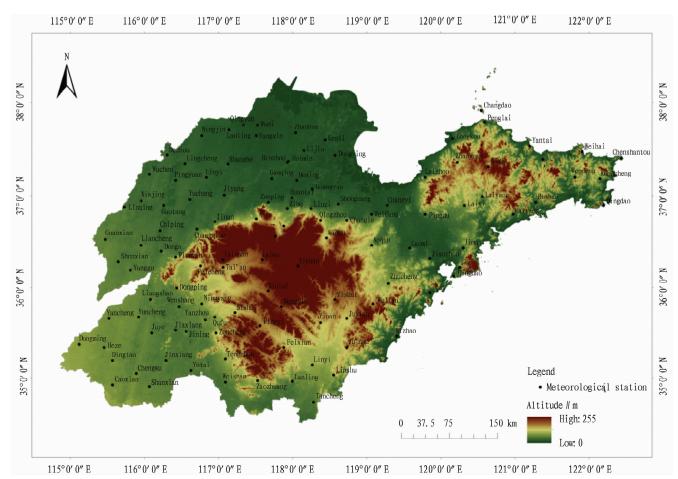


Fig. 1 Distribution of meteorological stations in Shandong Province

1.2 Research methods

1.2.1 Calculation method of SPI index. SPI index represents the probability of precipitation occurrence during the study period, and climate can be divided into nine grades according to SPI index (Table 1)^[5]. The precipitation data with skew probability distribution is normalized, and then SPI index is calculated using Gamma probability distribution. The formula is as follows:

$$f(x) = \frac{1}{\beta^{\alpha} \Gamma(\alpha)} x^{\alpha - 1} e^{\frac{-x}{\beta}} \tag{1}$$

Formula (1) is the probability density function of Gamma distribution, and α and β stand for shape and scale, which are estimated by the maximum likelihood method.

$$\alpha = \frac{1 + \sqrt{1 + \frac{4A}{3}}}{4A} \tag{2}$$

$$\beta = \frac{\overline{x}}{\alpha} \tag{3}$$

$$A = \lg \overline{x} - \frac{\sum_{i=1}^{n} \lg x_i}{n} \tag{4}$$

In formula (4), n is the number of time series; x is the precipitation at a specified time scale; \bar{x} is the average of precipitation series. Therefore, for the precipitation x_1 at a certain time scale, the probability of $x < x_1$ can be calculated as follows:

$$G(x < x_1) = \int_0^x f(x) dx \tag{5}$$

When x = 0, the probability is as follows:

$$G(x=0) = m/n \tag{6}$$

In formula (6), m represents the number of terms with precipitation of 0.

The results of formulas (5) and (6) are input into the normalized normal distribution function to get the formula:

$$G(x < x_1) = \frac{1}{\sqrt{2\pi}} \int_0^{x_1} e^{-SPI^2/2} dx \tag{7}$$

Approximate solution gives the following formula:

$$SPI = S \left\{ t - \frac{(c_2 t + c_1)t + c_0}{[(d_3 t + d_2)t + d_1]t + 1.0} \right\}$$
 (8)

In formula (8), $c_0 = 2.515517$, $c_1 = 0.802853$, $c_2 = 0.010328$, $d_1 = 1.432788$, $d_2 = 0.189269$, $d_3 = 0.001308$,

and
$$t = \sqrt{\ln \frac{1}{G(x)^2}}$$
.

In formula (7), if G(x) > 0.5, G(x) is 1 - G(x), and S = 1; if $G(x) \le 0.5$, S = -1.

In this paper, SPI-3 index, which is the SPI index of every three months from March to next February, was used to study the seasonal variation of dry and wet weather in Shandong Province. SPI-12 index, which is the SPI index of every year, was used to study the annual variation of dry and wet weather in Shandong Province.

1.2.2 Frequency of occurrence of dry and wet weather and proportion of drought-affected stations. The frequency of occurrence of dry and wet can represent the frequency of occurrence of dry and wet weather in a certain period of time, and the formula is as follows:

$$P = (n/N) \times 100\% \tag{9}$$

In formula (9), n is the number of years with dry and wet weather, and N is the number of time series studied.

Table 1 Standard of drought classification based on SPI index

SPI	Grade		
<i>SPI</i> ≥2.0	Extremely wet		
$1.5 \leqslant SPI < 2.0$	Severely wet		
$1.0 \leqslant SPI < 1.5$	Moderately wet		
$0.5 \leqslant SPI < 1.0$	Slightly wet		
-0.5 < SPI < 0.5	Normal		
$-1.0 < SPI \leq -0.5$	Slightly dry		
$-1.5 < SPI \le -1.0$	Moderately dry		
$-2.0 < SPI \leqslant -1.5$	Severely dry		
<i>SPI</i> ≤ -2.0	Extremely dry		

The proportion of drought-affected stations is the proportion of drought-affected stations to all stations in the study area in a certain period of time, which can represent the area affected by drought in a region, and the formula is as follows:

$$P_i = (k/K) \times 100\% \tag{10}$$

In formula (10), k is the number of drought-affected stations; K is the total number of stations in the study area; i represents the year.

1.2.3 Mutation test. In this study, sliding t test and pettitt test were used to verify the existence of mutation points. The moving t test $^{[14-15]}$ can be used to test a mutation point by examining whether there is a significant difference between the means of SPI sequences before and after the assumed mutation point. If there is a significant difference between the mean values, it can be considered that a mutation has occurred. The significance level of $\alpha = 0.05$ was adopted in this study.

pettitt test^[14,16] is used to detect a mutation point directly through SPI sequences. If the significance of statistics passes the test, the mutation point is significant; otherwise, it is not significant. The significance level of $\alpha = 0.05$ was also adopted here.

1.2.4 Wavelet analysis. Wavelet analysis^[17] can be used to determine periodic fluctuations at multi-time scales in SPI sequences and the distribution of these cycles in the study period. In this study, Morlet complex wavelet was adopted. The wavelet transform formula is as follows:

$$W_{\varphi}f(a, b) = |a|^{\frac{1}{2}} \Delta t \sum_{k=1}^{n} f(k\Delta t) \overline{\varphi}(\frac{k\Delta t - b}{a})$$
 (11)

In formula (10), a and b are expansion and displacement parameters, and $a \neq 0$; $\varphi(\frac{k\Delta t - b}{a})$ is a complex conjugate function of SPI sequence $f(k\Delta t)$.

Wavelet square difference is calculated according to the formula as follows:

$$Var(a) = \int_{-\infty}^{+\infty} |W_{\omega}f(a, b)|^2 db$$
 (12)

2 Results and analysis

2.1 Analysis of dry and wet climate characteristics of Shandong Province based on SPI index

2.1.1 Annual changes. The short-term variation of SPI index can reflect more obvious variation of dry and wet climate, while the

long-term variation of SPI index can more intuitively show the seasonal and annual alternation of drought and flood. Based on the monthly precipitation data of 116 meteorological stations in Shandong Province from 1970 to 2021, the SPI-12 index of each station was calculated according to formulas (1) - (7) firstly, and then the SPI-12 index of all stations was averaged to represent the annual SPI index of Shandong Province. As shown in Fig. 2, the dry and wet conditions in Shandong alternated dramatically year by year in the past 52 years, that is, several wet years often alternated with intense dry years. On the whole, there were more normal and light wet years in the province. In terms of annual variation, the climate was mostly normal or wet in the 1970s, that is, there were less dry years, more normal years, and some moderately wet years. In the 1980s, it was severely dry in many years. In the 1990s, dry years alternated with wet years. In 1990, annual SPI index rose sharply, and the climate was severely wet, which alleviated the drought in the first 10 years. Dry years alternated with wet years in the next 9 years. After the 2000s, there were mainly wet years on the whole except for an extremely dry year 2002 with the SPI index of -2.23, and the year 2003 was an extremely wet year. After 2010, dry years alternated generally with wet years, SPI index was up to 2.23 in 2021, so the year was an extremely wet vear.

The tendency rate of annual variation in SPI index was obtained by linear fitting. If the tendency rate of annual variation is greater than 0, the annual SPI index has an upward trend, that is, the climate in the region tends to be wet, and vice versa, it tends to be dry. As can be seen from Fig. 2, the tendency rate of annual variation in SPI index in Shandong Province was 0.066/10 a, that is, the climate tends to be wet slightly.

2.1.2 Seasonal changes. According to the above method of studying the annual changes, the seasonal SPI-3 index of each station

was used to analyze the dry and wet climate characteristics of Shandong in four seasons. As shown in Fig. 3, the dry and wet conditions in Shandong in four seasons in Shandong Province also changed dramatically during 1970 – 2021. In the 1970s, both summer and autumn in Shandong Province were relatively normal or wet, and severe flood was more likely to occur in summer, while more intense drought was more likely to occur in spring and winter. In the 1980s, Shandong Province experienced severe drought in most seasons except for autumn with alternating dry and wet climate. In the 1990s, summer and winter were dry in Shandong Province. In the 2000s, spring and summer were wetter in Shandong Province, while dry and wet climate alternated in autumn, and the climate was normal in winter. After 2010, spring drought dominated Shandong Province.

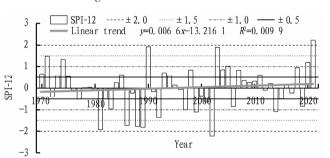
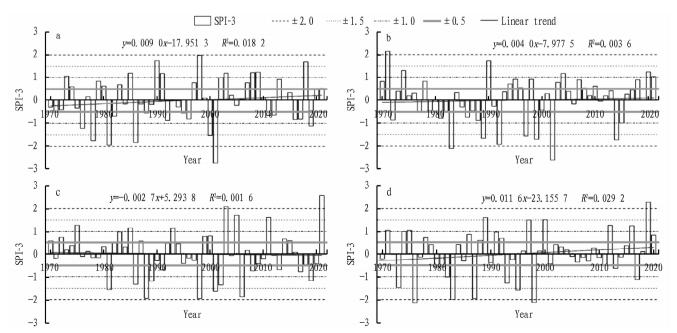


Fig. 2 Annual changes of SPI index in Shandong Province from 1970 to 2021

As shown in Fig. 2, the tendency rate of seasonal variation in SPI index in spring, summer and winter was 0.09/10~a, 0.04/10~a and 0.12/10~a, respectively, showing a wet trend. Among them, the upward trend in summer was the weakest and the strongest in winter. In autumn, it was -0.027/10~a, showing a dry trend.



Note: a. Spring; b. Summer; c. Autumn; d. Winter.

Fig. 3 Changes of SPI index in four seasons in Shandong Province from 1970 to 2021

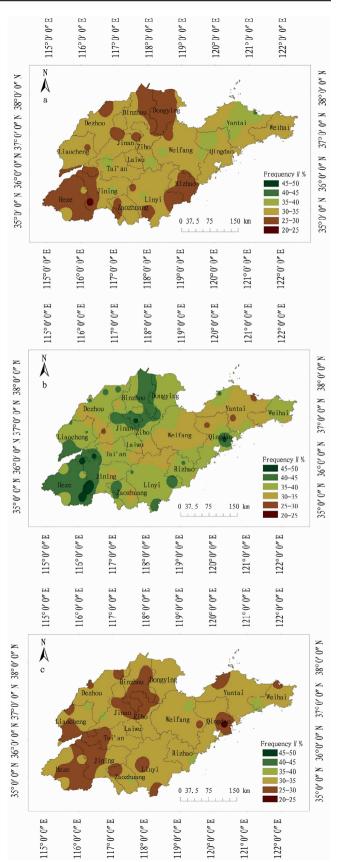
2.2 Frequency of dry and wet climate and influencing range of drought

Frequency of dry and wet climate. Statistical analysis was 2.2.1 made on SPI index at annual and seasonal scales, and the frequency of dry and wet climate of different grades was obtained (Table 2). At the annual scale, the proportion of normal years was the highest, up to 38.46%, followed by slight wet years. In summer, autumn and winter, the proportion of normal climate was the highest, followed by slight wet climate. In autumn, the frequency of normal climate was the highest, reaching 46.15%. In spring, the proportion of wet climate was the highest, up to 34.62%, followed by slight drought. On the whole, the proportion of dry or wet climate was higher in spring than the other three seasons, indicating that spring was more prone to drought or excessive wet climate. The frequency of extremely wet climate was the highest in autumn. That of severely wet, moderately wet, or slight drought in spring was much higher than the other three seasons. Slightly wet climate was more common in summer. The frequency of moderate drought was higher in autumn and winter. Severe drought occurred more frequently in summer and autumn. Extreme drought occurs in summer and winter. Generally speaking, severe drought appeared frequently in summer in Shandong Province.

Table 2 Frequency of dry and wet climate in Shandong Province

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Grade	Annual	Spring	Summer	Autumn	Winter	
Extremely wet	1.92	0	1.92	3.85	1.96	
Severely wet	3.85	5.77	1.92	3.85	3.92	
Moderately wet	7.69	11.54	7.69	5.77	9.80	
Slightly wet	21.15	17.31	21.15	15.38	13.73	
Normal	38.46	32.69	42.31	46.15	45.10	
Slightly dry	9.62	19.23	11.54	7.69	7.84	
Moderately dry	7.69	3.85	0.00	7.69	7.84	
Severely dry	7.69	7.69	9.62	9.62	5.88	
Extremely dry	1.92	1.92	3.85	0	3.92	

Shandong Province has a special geographical position, with the coexistence of inland and coastal areas, and there are obvious regional differences in precipitation. Due to factors such as the diversification of landform and differences in underlying surfaces, the distribution of dry and wet climate in Shandong Province is complicated and not uniform in space. Based on SPI-12 index, the climate in Shandong Province during 1970 - 2021 was divided into three grades: dry, normal and wet climate, and the spatial distribution was obtained by drawing a coloring map (Fig. 4). It can be seen from Fig. 4a that the frequency of wet years in Shandong Province ranged from 20. 29% - 42. 45%, and the frequency of wet years in Jining, northwest Qingdao and central Yantai was higher. The frequency of wet years in Yantai station was the highest, reaching 40.38%. As shown in Fig. 4b, the frequency of normal years in Shandong Province was between 22.70% and 61.20%, generally higher than that of wet or dry years. It was higher mainly in the west and north of Shandong Province, including Heze, Liaocheng, Binzhou, Dongying, northern Zibo and eastern Jinan, among which the frequency of normal years in Yangxin station in Binzhou City was the highest, and that of Boxing Station in Heze



Note: a. Wet; b. Normal; c. Dry.

Fig. 4 Spatial distribution of drought frequency in Shandong Province

City also reached 46.15%. As shown in Fig. 4c, the frequency of drought years in Shandong Province from 1970 to 2021 ranged from 20.00% to 38.80%, and it was higher mainly in the south and northwest of Shandong Province. The frequency of drought in Zhucheng station in Weifang City was up to 38.46%, and that of Linyi station in Dezhou City also reached 36.54%.

2.2.2 Ratio of drought stations. In meteorological terms, if the ratio of drought stations R in a certain year in a region is greater than 50%, it is considered that global drought occurred in the region in the year. If $33\% < R \le 50\%$, regional drought appeared in the year. If $25\% < R \le 33\%$, partial regional drought occurred in this year. If $10\% < R \le 25\%$, local regional drought happened in that year. If $R \leq 10\%$, there was no significant drought in that vear^[14,18-20]. Fig. 5 shows the ratio of drought stations and its linear fitting curve in Shandong from 1970 to 2021. It can be seen that the ratio of drought stations in Shandong Province changed dramatically year by year. It was low in two to three years, then became high suddenly, and finally declined rapidly. In the past 52 years, there was no obvious drought in Shandong Province, and in the drought years, there was mainly local and global drought. Among them, the number of years with global drought was 13, and it mainly appeared from 1980 to 2003, with a frequency of 25.00%. Regional drought occurred in 6 years, with a frequency of 11.54%. Partial regional drought appeared only once, and the frequency was 1.92%. Local drought occurred 17 times, with a frequency of 32. 69%. There were 15 years without obvious drought, and the frequency was 28.85%. The drought was mainly light and moderate drought. In the past 52 years, the change tendency rate of the ratio of drought stations in Shandong Province was -0.48/10 a, and the drought area showed a decreasing trend.

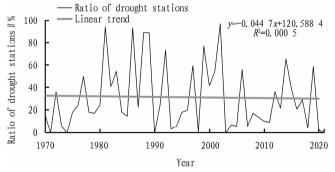


Fig. 5 Ratio of drought stations in Shandong Province from 1970 to 2021

2.3 Periodic changes of wet and dry climate Morlet wavelet transform was applied to the annual sequence of SPI index in Shandong Province from 1970 to 2021. The real part isoline map of wavelet coefficient can represent the annual distribution of SPI index in the study period. The positive center of isolines indicates that the annual SPI index is positive in the corresponding period, that is, the climate in Shandong is humid in this period, and vice versa. From the distribution of isolines of wavelet coefficient in Fig. 6a, it can be found that in recent 52 years, the annual variation of SPI index had four periods, including short periods of 2 – 5 and 6 – 10 a, medium period of 12 – 15 a and long period of

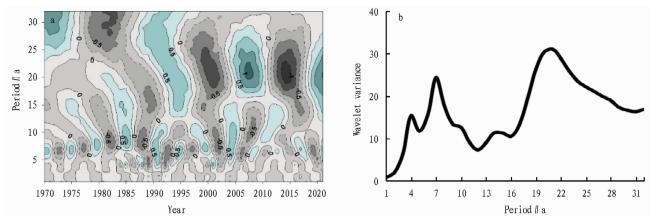
20-30 a. The short period of 2-5 a had quasi-18 times of alternation between dry and wet climate. The short period of 6-10 a had quasi-11 times of alternation between dry and wet climate. The middle period of 12-15 a had quasi-6 times of alternation between dry and wet climate. The long period of 20-30 a had quasi-4 times of alternation between dry and wet climate. In a long period, dry periods were mainly distributed during 1985-1993, 1997-2002 and 2010-2018, while wet periods mainly appeared during 1970-1975, 1990-1996 and 2005-2010. During the study period, dry and wet processes in a long period were stable and global, and the wet period was still not closed and continued in 2021. Therefore, it can be inferred that Shandong would experience a relatively continuous wet period.

Wavelet variance can characterize the distribution of wavelet energy of annual SPI index with years to determine the main period, and can judge the future change trend of SPI index in different periods. As shown in Fig. 6b, the wavelet variance curve of annual SPI index in Shandong Province had four significant peaks, with time scales of 4, 7, 14 and 21 a. Among them, the long period of 21 a was the most significant, and was the first main period. The periods of 7 and 4 a were the second and third main period, and the period of 14 a was the fourth main period. It shows that the fluctuation of these four periods affected the changes of dry and wet climate in Shandong in the whole time series. From the distribution of the real part of wavelet coefficient in Fig. 6a, it can be inferred that in the first main period of 21 a, Shandong Province will continue to have a wet or normal climate. For the second main period of 7 a, dry and wet climate will alternate continuously.

2.4 Mutation test of SPI index The sliding t-test method was used to test whether SPI index had a mutation point in Shandong Province from 1970 to 2021, and the pettitt test method was used to verify the mutation point. As shown in Fig. 7, through both the sliding t-test and the pettitt test, it is concluded that the year 2003 was the mutation point, that is, there was a sudden change of annual SPI index in Shandong Province in 2003 during 1970 – 2021.

2.5 Temporal and spatial changes of dry and wet climate characteristics before and after the abrupt change

2.5.1 Temporal changes. There was an abrupt change of SPI index in Shandong Province in 2003, so the dry and wet climate characteristics before and after 2003 were analyzed. From 1970 to 2002, the annual average precipitation in Shandong Province was 639.6 mm. After the abrupt change in 2003, the annual average precipitation from 2004 to 2020 was 701.9 mm, increasing by 62.3 mm. Fig. 8 shows the tendency rate of annual SPI index in Shandong Province before and after the abrupt change. It can be found that in the 33 years before 2003, the tendency rate of annual SPI index was -0.24/10 a, and showed a downward trend, indicating that the climate of Shandong Province was arid in the 33 years before the abrupt change. In the 18 years after the abrupt change, the tendency rate of annual SPI index was 0.10/10 a, and showed an upward trend, revealing that the climate of Shandong Province became wet in the 18 years after the abrupt change.



Note: a. Wavelet real part isoline; b. Wavelet variance diagram.

Fig. 6 Wavelet change of annual SPI index in Shandong Province during 1970 - 2021

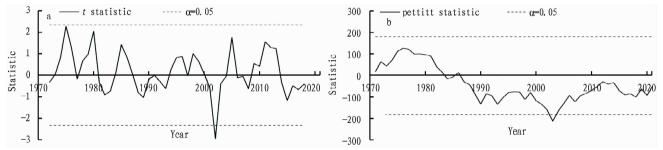


Fig. 7 Sliding t-test and pettitt test of annual SPI index in Shandong Province from 1970 to 2021

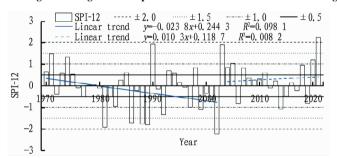


Fig. 8 Tendency rate of annual SPI index in Shandong Province before and after the abrupt change

- **2.5.2** Spatial changes. The spatial pattern of the frequency of dry and wet climate before and after the abrupt change in 2003 was analyzed.
- **2.5. 2. 1** Before the abrupt change. From Fig. 9a, it can be found that the frequency of wet years in Shandong Province during 1970-2002 was 12.13%-39.39%, and the frequency of wet years in Taian, Laiwu, Yantai and other regions was higher. Among them, the maximum appeared in stations Penglai, Pingdu and Yantai, reaching 39.39%, and Jinxiang station had the least wet years, with the frequency of only 12.13%.

Fig. 9b shows that the frequency of normal years in various regions of Shandong Province before the abrupt change ranged from 24.24% to 54.54%. The frequency of normal years was high mainly in the northeast of Jinan – Jiaozhou – the north of Zibo, Heze – the west of Jining and around Qingdao station, among which it was the highest in stations Jimo, Heze and Laoshan, ex-

ceeding 50%.

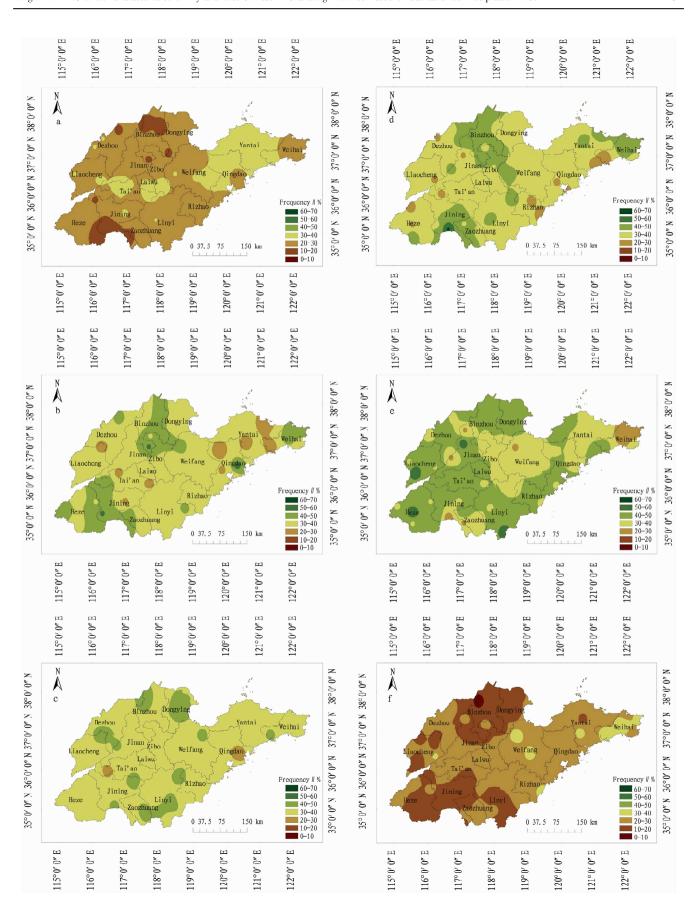
As shown in Fig. 9c, the frequency of dry years before the abrupt change ranged from 21. 22% to 48. 48%, generally higher than that of wet years. It can be seen that the regions with high frequency of dry years before the abrupt change had a large area, among which the maximum appeared in stations Wudi, Qingyun and Jinan, reaching more than 45.00%.

2.5.2.2 After the abrupt change. Fig. 9d – Fig. 9f show the spatial distribution of dry and wet climate in Shandong Province from 2004 to 2021 after the abrupt change. Fig. 9d reveals that after the abrupt change, the frequency of wet years in various regions of Shandong Province varied from 22.26% to 61.09%, and some regions, such as Jining, Zaozhuang – Binzhou, and Weihai, had the highest frequency of wet years.

As shown in Fig. 9e, the frequency of normal years in various regions of Shandong Province after the abrupt change ranged from 22.22% to 55.54%. The frequency was generally the same before and after the abrupt change, but the area of high-frequency regions expanded, indicating that the number of areas with normal years increased after the abrupt change. However, the frequency distribution of dry years is just the opposite.

Seen from Fig. 9f, the frequency of drought in various regions of Shandong Province decreased to 5.57% -38.89% after the abrupt change, and the area of high-frequency regions reduced, showing that there were fewer areas with frequent dry years after 2003.

2.5.2.3 Difference. Fig. 9g – Fig. 9i show the difference in the frequency of wet, normal and dry years before and after the abrupt



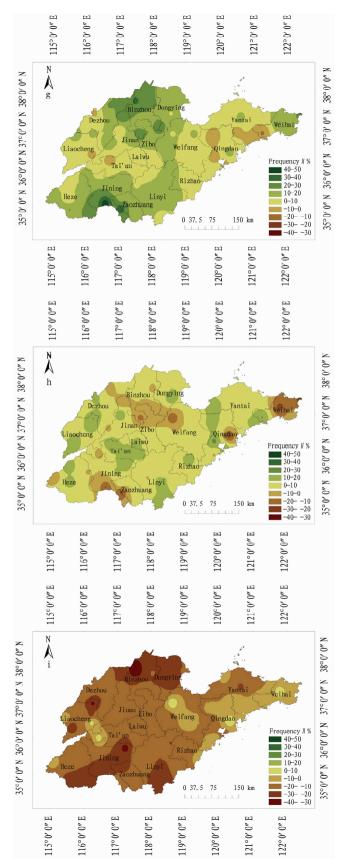


Fig. 9 Spatial distribution of dry and wet climate in Shandong Province before and after the abrupt change

change.

Seen from Fig. 9g, the difference in the frequency of wet years was positive in most regions, indicating that the frequency of wet years in Shandong increased on the whole, and the increase in the frequency of wet years in Binzhou, Jining and Zaozhuang was the most obvious. Among them, the increase was up to 45.96% in Yutai station.

As shown in Fig. 9h, the frequency of normal years also showed an increase trend in most regions, and showed a decrease trend in sporadic regions such as Weifang, Weihai, Qingdao, Jining and Zaozhuang, but the increase in most regions remained in the range of 0-10.00%.

Fig. 9i shows that the frequency of dry years in most regions of Shandong Province declined after the abrupt change except for sporadic areas with an increase of 0-10.00%. Especially in Binzhou – Dongying, Jining and Yantai, the decrease was the largest, and the maximum appeared in Wudi station, reaching – 39.90%. Therefore, from the spatial distribution, it can also be seen that after the abrupt change in 2003, the normal and humid areas in Shandong Province increased, and the frequency of wet years increased greatly, which is consistent with the conclusion that Shandong Province would become humid.

3 Conclusions

Based on the precipitation data of 116 stations in Shandong Province from 1970 to 2021, the SPI index in a year and four seasons was calculated to analyze the temporal and spatial distribution of dry and wet climate, and its periodicity was analyzed by Morlet wavelet change. The sliding t-test and pettitt test were used to test the mutation of annual SPI index, and the temporal and spatial changes of dry and wet climate characteristics before and after the abrupt change were analyzed.

- (1) In Shandong Province, there were more normal or wet years, and the climate tended to be wet. Before 2003, dry and wet climate appeared alternately. Drought was the most severe in the 1980s, and then wet years were dominant. The SPI index in spring, summer and winter showed an upward trend, and wet climate showed an increasing trend. In autumn, there was a weak dry trend. Light drought occurred frequently in spring, and moderate drought mainly appeared in autumn and winter; severe drought was common in summer and autumn, and extreme drought appeared frequently in summer and winter.
- (2) For the time series, the occurrence frequency of normal years was the highest in Shandong Province, followed by slightly wet climate. As for the spatial distribution, the climate was normal or slightly wet in most regions of Shandong Province, and the frequency of wet years was higher in central and northeast Shandong and the peninsula, while the climate was normal in the southwest and north of Shandong. There were few regions with dry years, and they were mainly located in the northwest of Shandong Province.
- (3) Through Morlet wavelet change, it is found that the first main period of 21 a existed in Shandong Province. On this scale, Shandong province experienced quasi-4 times of alternation between dry and wet climate. In the next period of time, Shandong would enter a more continuous wet period. The year 2003 was

identified as the mutation point by sliding t-test and pettitt test.

(4) After the abrupt change, the precipitation in Shandong Province increased significantly. In terms of time series, SPI index changed from decreasing to increasing. In terms of spatial distribution, after the abrupt change, the areas with normal and wet years increased, while the areas with dry years decreased, and the frequency of wet years rose greatly. The characteristics of dry and wet climate changed from gradually drying to wetting.

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(From page 5)

4 Conclusions and discussion

- (1) The hail weather mainly occurred during the eastward movement of the upper air trough accompanied by the shear line. The shear line presented a forward tilt, and the forward tilt situation intensified. As a result, the cold dry air behind the upper shear line was placed on top of the warm and humid air in front of the lower shear line, and the wind shear in the vertical direction strengthened, increasing the convective instability of the air column over Ulanqab City, which was conducive to the triggering and development of hail weather with strong convection.
- (2) The water vapor channel of this hail and other strong convection weather was the main transport channel for water vapor in summer: water vapor was transported northeastwards from the Bay of Bengal, India and Nepal over the Himalayas. Before the strong convection occurred, the specific humidity increased obviously. The relative humidity was better in the lower layer, and the dry cold air was invaded in the upper layer.
- (3) From the configuration of upper and lower wind fields, and profiles of vertical velocity and relative humidity, it can be seen that the suction effect of the upper-level jet stream in Ulan-

qab City strengthened upward movement, and the negative vertical velocity indicates that there was a strong upward movement. The profile of relative humidity shows that there was obvious convective unstable stratification

(4) It can be seen from the radar echo maps that the hook echo gradually split into several strong convection cells, and moved eastwards to gradually affect most of the city and bring a large-scale hail to the city. It was accompanied by short-term heavy precipitation. The parameters of radar echo characteristics, such as combined reflectivity, vertically integrated liquid, and echo top height, increased significantly before and during the occurrence of hail, which had good indicative significance for the prediction and early warning of hail.

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