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Temporal and Spatial Analysis of Temperature and Precipitation in Henan Province

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ABSTRACT: Using the monthly precipitation data of 15 national basic meteorological stations in Henan Province from 1960 to 2021, the MK abrupt change test and EOF analysis were used to analyze the trend of temperature and precipitation. The results show that: (1) The temperature and precipitation in Henan Province from 1960 to 2021 show an overall upward trend. (2) The M-K test of annual temperature shows that the temperature rose significantly in the mid-1990s. (3) EOF mode 1 can better reflect the main spatial and temporal features of Henan Province, with the temperature type showing a cold (warm) pattern throughout the province. (4) The precipitation in Henan Province shows two types of precipitation throughout the year: abundant or scarce precipitation. The high value area is located in the southeast region, and the fluctuation in the southeast region is higher than that in the northwest region, with a high degree of change, and the central region is a transition area.

KEYWORDS: climate change; Temperature and precipitation; M-K test; EOF

1. INTRODUCTION

Climate change is still a hot topic, and frequent extreme weather and climate events around the world have seriously damaged the ecological environment and human society (Robinson, 2021; Dai et al., 2023). The Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC), published in March 2023, shows that global surface temperatures in 2011-2020 were 1.09° C higher than in 1850-1900, with land (1.59°C) rising more than the oceans (0.88° C) (IPCC, 2023). In particular, the rate of global warming after 1970 was faster than in any previous 50 years (IPCC, 2023). The increasing frequency and intensity of warming, changing precipitation patterns and extreme weather events since the 1950s have led to reduced food security and water supplies, increased risks to health, livelihoods, economic growth and social stability, and hindered efforts to achieve the Sustainable Development Goals (IPCC, 2023). Today, climate change and extreme weather are increasingly causing displacement, widespread and irreversible losses to human systems in places such as Africa, Asia, and North America, and altering terrestrial, freshwater, coastal, and high seas ecosystems worldwide (IPCC, 2023).

Henan Province is in a transitional phase between north and south in terms of climatology and is very sensitive to climate change (Li et al., 2019). In July 2021, Henan Province suffered catastrophic heavy precipitation. The average maximum daily precipitation in Henan Province on July 20 was 93.0 mm (Huang et al., 2022), and the maximum hourly precipitation in Zhengzhou meteorological station exceeded 201mm (Wu et al., 2023), causing 14.76 million people to be affected and 398 people to be killed or missing. Economic losses exceeded 120 billion yuan. In 2014, 14.62 million people in Henan Province suffered the worst drought in 63 years, and agricultural losses amounted to 3.377 billion yuan, accounting for 84% of the direct economic losses of 4.09 billion yuan (Luo et al., 2020). This study is helpful to understand the weather change law and extreme weather events in Henan Province, so as to advance warning and prevention, and the results can also provide scientific basis for resource production and utilization, urban evolution and development, and disaster prevention in Henan Province.

2. STUDY AREA AND DATA SOURCE

2.1 Research Area

The study area is Henan Province. From west to east longitude 110°21 ', east to east longitude 116°39 ', across longitude 6°18 ', the linear distance of Henan Province is about 580 kilometers; South from 31°23 'north latitude, north to 36°22' north latitude, cross latitude 4°59 ', the linear distance of about 550 kilometers. It borders Shandong and Anhui to the east, Shaanxi to the west, Hebei and Shanxi to the north, and Hubei to the south; The total area of the province is 167,000 square kilometers. The terrain is looking north to south, connecting east to west, the terrain is high in the west and low in the east, composed of plains and basins, mountains, hills and water; It spans Haihe River, Yellow River, Huaihe River and Yangtze River. Most of Henan Province is located in the warm temperate zone, and the south is trans-subtropical, which belongs to the continental monsoon climate of the transition from the north subtropical zone to the warm temperate zone. At the same time, it also has the characteristics of the transition from the plain to the hilly mountain climate from east to west, with the characteristics of four distinct seasons, the same period of rain and heat, complex and diverse, and frequent meteorological disasters.

2.2 Data Sources

In order to ensure the synchronization of data at each station and establish a relatively complete climate series, monthly air temperature and precipitation data of 15 national basic meteorological stations in Henan Province from 1960 to 2021 are selected in this paper. There are few missing measurement data in this time span, and average interpolation is used to process a few missing measurements. The temperature and precipitation data are all from China Meteorological Data network http://data.cma.cn/. The distribution and geographical location of meteorological stations are shown in Figure 1.

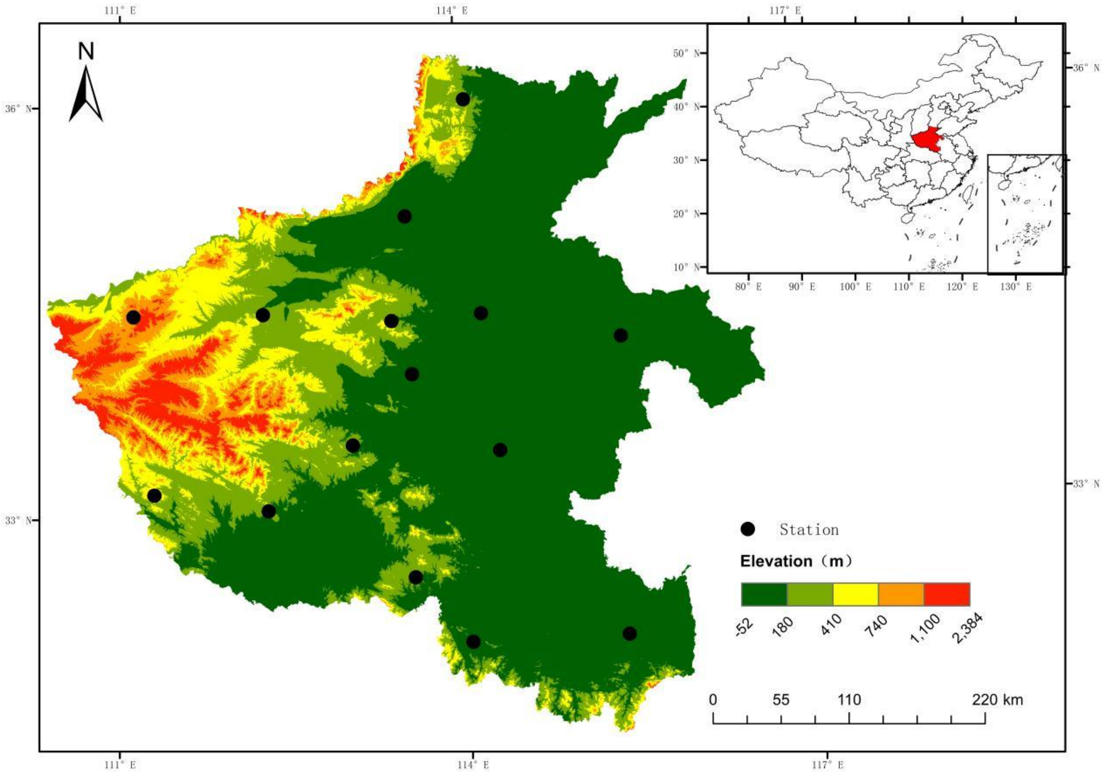


Figure 1. Overview of The Study Area

3. RESEARCH METHODS

3.1 Data Preprocessing

In the selection of meteorological stations, meteorological stations lacking measurement data were screened, meteorological stations with a lot of missing measurement data were excluded, and national basic meteorological stations were selected. Finally, 15 national basic meteorological stations with few missing measurement data from 1960 to 2021 were selected, and the data came from the national website with strong reliability. The data are the monthly average temperature and precipitation. Inevitably, there are still 34 months of precipitation missing in each station, and most of the missing months are January, April and December. The missing test value is concentrated and the month is single, so the average value interpolation method is adopted, and the average value of each station in the same year and month is used to interpolate the missing test value.

In this paper, the annual generations in Henan Province from 1960 to 2021 are divided into six stages: 1960-1969, 1970-1979, 1980-1989, 1990-1999, 2000-2009 and 2010-2021.

In order to reflect the trend trend of temperature and precipitation data on time scale, the linear correlation curve fitting was carried out, and the overall trend of time scale was obtained. The anomaly value is used to reflect the cold, warm, dry and wet temperature and precipitation of each decadal in the whole time scale. The average annual temperature and precipitation are averages of the average temperature for each month. The average seasonal temperature and precipitation are the average monthly values of each season. In the interannual time scale, the data cages of 15 meteorological stations were combined to represent the average annual moderate precipitation of Henan Province. In the spatial interpolation, inverse distance weighted interpolation (IDW) was selected to interpolate the climate data of 15 meteorological stations to reflect the overall spatial trend of Henan Province.

3.2 Data Processing

3.2.1mann-Kendall Test Method

Mann-Kendall test method (Kendall, 1975; Mann, 1945) is a climate diagnosis and prediction technique used to determine whether there is a sudden change in climate, and to determine the time when the sudden change will occur.

Mann-Kendall test for time series X={x1, x2,... , x3} construct statistics:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \mathrm{sgn}(x_j - x_k)$$

Where “n” is the number of observations, “xj” and “xk” are observations, and “sgn” is expressed as follows:

$$\mathrm{sgn}(x_j - x_k) = \begin{cases} 1 \ \ (x_j - x_k > 0) \\ 0 \ \ (x_j - x_k = 0) \\ -1 \ (x_j - x_k < 0) \end{cases}$$

S is a normal distribution with a mean of 0 and a variance of:

$$\mathrm{Var}(S) = \frac{n(n-1)(2n+5)}{18}$$

When n > 10, the standard normal statistical variable is calculated by the following formula:

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & (S > 0) \\ 0 & (S = 0) \\ \frac{S+1}{\sqrt{Vae(S)}} & (S < 0) \end{cases}$$

In the trend test, if |Z|≥Z_(1-α/2) at a given α confidence level, then the null hypothesis is unacceptable. For statistical variable Z greater than 0, it is an upward trend, and less than 0, it is a downward trend. Absolute values of Z greater than or equal to 1.28, 1.64, and 2.32 indicate that they pass the significance test with confidence of 90%, 95%, and 99%.

When the test sequence mutation analysis is further carried out, the statistic is different from the above Z, and an order column is constructed for the time series X of n sample sizes:

$$S_k = \sum_{i=1}^{k} r_i, \quad k=2,3 \ldots, \quad n$$

Statistics are defined under the assumption of random independence of time series:

$$UF_k = \frac{S_k - E(S_k)}{\sqrt{\mathrm{Var}(S_k)}}, k = 1,2, \quad \ldots, \quad n$$

Among them：

$$E(S) = k(k+1)/4$$

$$\mathrm{Var}(S) = \frac{k(k-1)(2k+5)}{72}$$

Repeat the process according to time series X inverse time series to get UB_k, analyze and draw the graph of UF_k and UB_k. If UF_k is greater than 0, it indicates an upward trend, and vice versa. When they exceed the critical line, the trend is significant, and the exceeded range is identified as the time region in which the mutation occurs. If two lines intersect, and the intersection point is between the critical line, it indicates that the moment is the beginning time of mutation.

3.2.2 Empirical Orthogonal Function (EOF)

empirical orthogonal function analysis, also known as principal component analysis, is a method that analyzes structural features in matrix data to extract the main data feature quantities. The eigenvector corresponds to the spatial sample, also known as the spatial mode (EOF), which reflects the spatial distribution characteristics of the element field to a certain extent. The principal component corresponds to the time change, also known as the time coefficient (PC), which reflects the weight change of the corresponding spatial modes with time.

Therefore, EOF analysis is called spatiotemporal decomposition, that is, X=EOF×(m×n)P×C(m×n), where m is the number of sites and n is the number of years.

4. RESULTS AND DISCUSSION

4.1. Interannual Variation

4.1.1 Time Analysis

(a) (b)

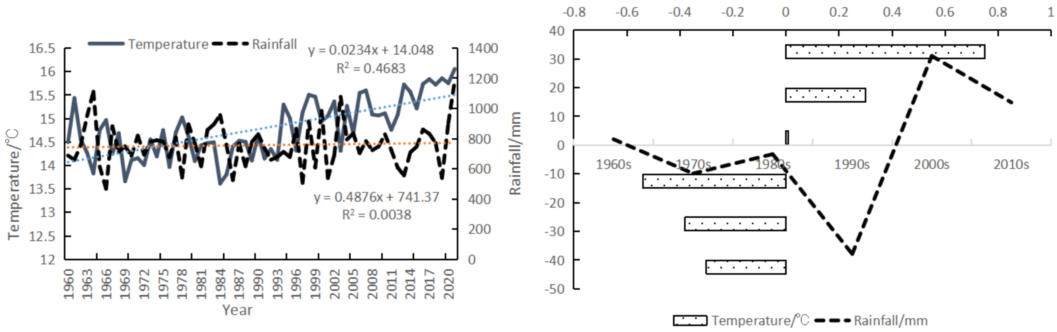
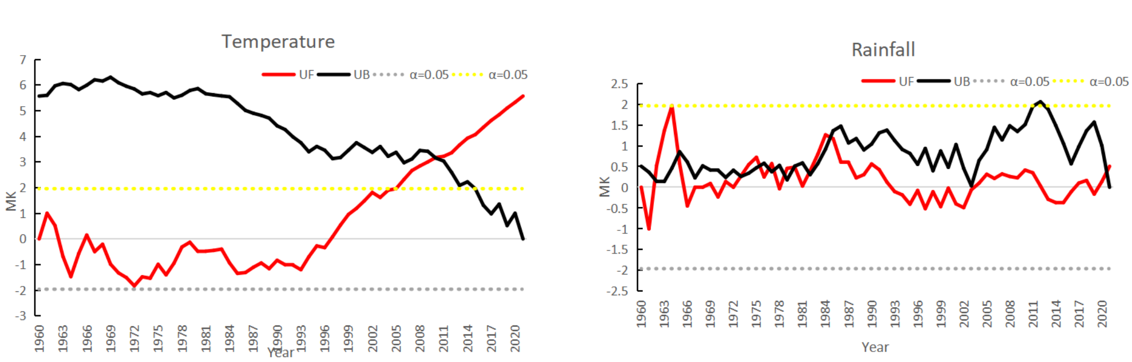


Figure 2. (A) Interannual Changes Of Temperature And Precipitation In Henan Province During 1960-2021. (B) Interdecadal Anomaly Values Of Temperature And Precipitation In Henan Province

From the inter-annual scale, the overall temperature and precipitation in henan province during 1960-2021 showed an upward trend (FIG. 2a). The average temperature during 62a was 14.79℃, with a temperature increase of 0.23℃/10a. The maximum monthly average temperature was 30.2℃ in June 1961, and the minimum monthly average temperature was -4.3℃ in February 1964. From the perspective of annual temperature, the average annual temperature in 2021 is the highest 16.06℃, and the lowest average annual temperature in 1984 is 13.61 ℃, with a difference of 2.45℃. The average annual precipitation of 62a is 756.73mm, and the precipitation increase is 4.88mm/10a. The maximum annual average precipitation of 1180.89mm occurs in 2021, which is 714.34mm different from the lowest annual average precipitation of 466.65mm in 1966, and the maximum monthly precipitation of 902.4mm occurs in the same year (2021). The extreme rainfall is modulated in part by changes in the latitude position of the western North Pacific monsoon trough (Huang et al.2022). On the interdecadal scale, the temperature anomaly in Henan Province (FIG. 2b) was negative from the 1960s to the mid-1990s, and began to turn positive and increase in magnitude after the mid-decade, which is similar to the interdecadal temperature change in China from 1951 to 2018. The overall precipitation anomaly fluctuates greatly. From 1990s to early 21st century, there is a large difference in precipitation anomaly. In the first 20 years of 21st century, the precipitation anomaly increases significantly.

4.2 Mk Mutation Test Of Temperature And Precipitation

（a） （b）



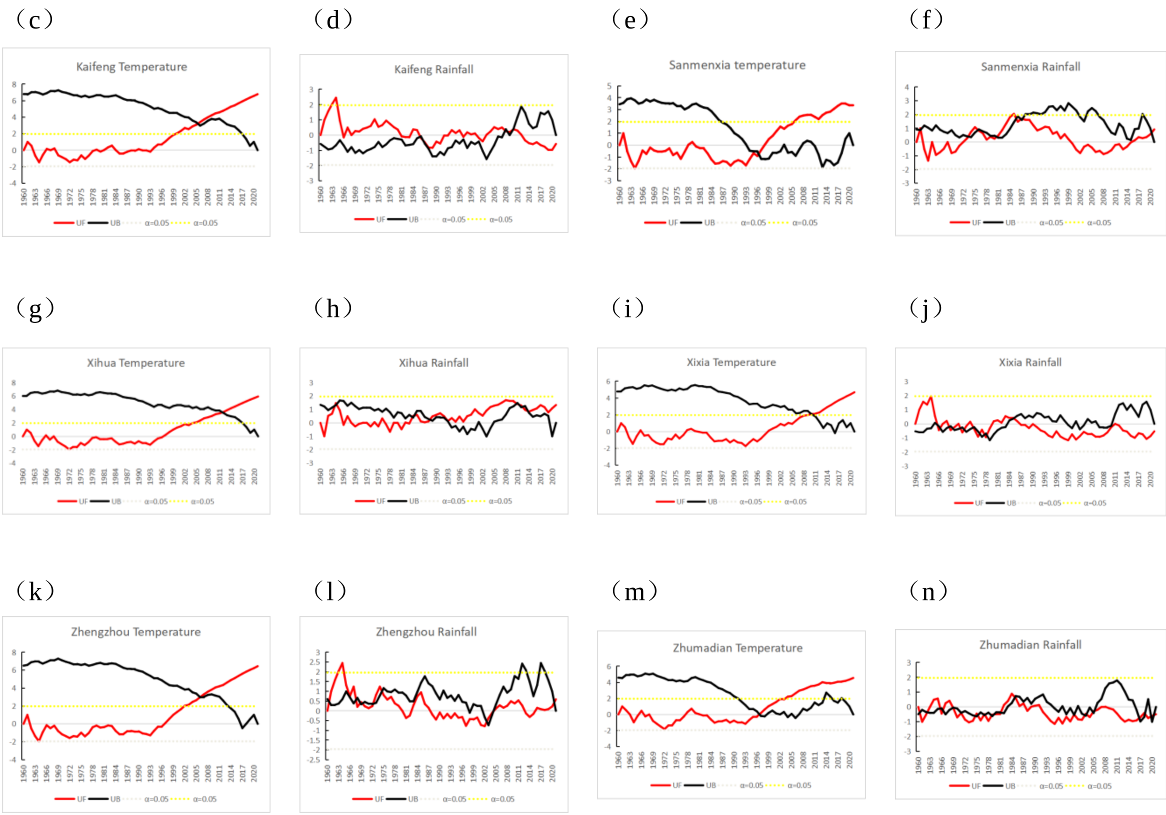


Figure 3. Mk Curves Of Temperature And Precipitation In Henan Province And Representative Stations During 1960-2021

In order to test the significance and mutation time of the trend of temperature and precipitation in the past years, the mutation test of the average annual mild annual precipitation in Henan Province from 1960 to 2021 was conducted. Chart 3 (a) of the M-K test of past temperature shows a significant upward trend in the mid-1990s, which is the same period as the global warming beginning in the 1990s (Fang et al., 2017), possibly due to the westward and southward extension of the Western Pacific Subtropical High while strengthening. As a result, the Siberian high Pressure and the winter monsoon are weakened, and the frequency of cold air entering the southwest is reduced. (Ma et al, 2013) In the confidence interval, UF and UB did not intersect in the confidence interval, so the annual average temperature rising trend did not change significantly. In terms of precipitation, the fluctuation changes. In Figure 3 (b), UF and UB curves intersect 12 times in the confidence interval, and the mutation years are mostly concentrated in 1973-1985.

The mutation trend time of each station was detected, and MK mutation test was conducted on the temperature and precipitation data of each station. The representative stations were shown in Figure 3 (c-n). In terms of temperature, the trend time of temperature rise at each station is consistent with the temperature rise of the whole province in the late 1980s to the early 1990s, and the abrupt change time is mostly in the late 1990s and around the 2010s. The precipitation MK mutation test is different, and like the Z-value test, most of them fail to pass the significance test.

4.3 Eof Analysis

Table 1. Contribution Rates Of Eof4 Main Modes Of Temperature In Henan Province

Modes	Eigenvalue	Variance contribution rate	Cumulative variance contribution rate	Lower limit of error	Upper limit of error
1	5.86284	0.87568	0.87568	3.72203	8.00365
2	0.28384	0.04239	0.91807	0.18019	0.38749

3	0.19785	0.02955	0.94762	0.12561	0.27010
4	0.08582	0.01281	0.96044	0.05448	0.11717

In order to extract the typical characteristics of temperature in Henan Province, EOF decomposition was applied to conduct spatio-temporal decomposition of temperature in Henan Province from 1960 to 2021, and four main modes were obtained (Table 1), with a cumulative contribution rate of 96.04%. However, only the first two modes' error ranges did not overlap and passed the North significance test, and the contribution rates of the two modes were 87.57% and 4.24%, respectively. It can be seen that mode I can better reflect the main spatial and temporal characteristics of Henan Province. Temperature EOF1 is positive, so the temperature type of Henan Province is cold (warm) in the whole region. The high value area appeared in the Kaifeng area of Zhengzhou, and gradually decreased around, while the low value area appeared in Sanmenxia, Xuchang, Shangqiu and other areas. In the time series, the temperature also shows a general upward trend, which is consistent with global warming.

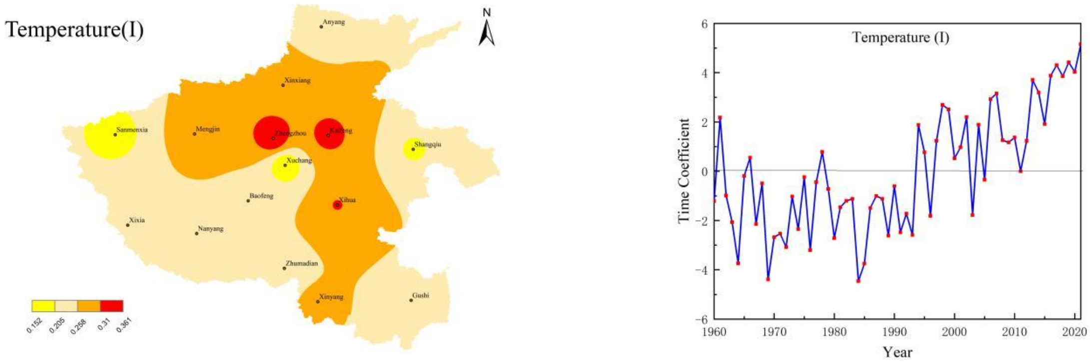
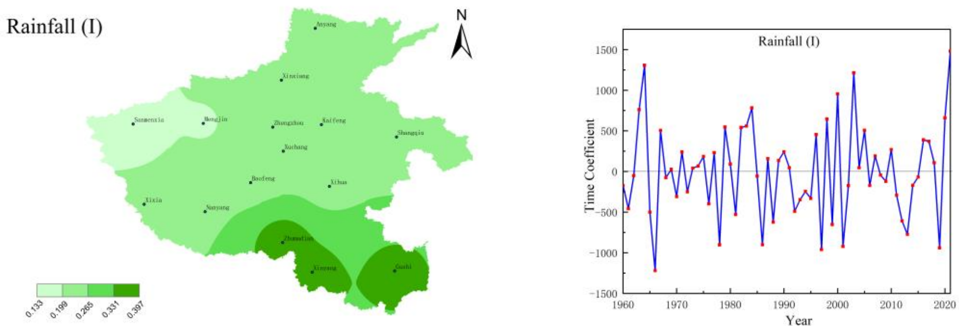


Figure 4. Eof1, The First Mode Of Temperature In Henan Province During 1960-2021

Table 2. Contribution Rates Of Eof5 Main Modes Of Precipitation In Henan Province

Modes	Eigenvalue	Variance contribution rate	Cumulative variance contribution rate	Lower limit of error	Upper limit of error
1	322575.2	0.535617	0.5356	204787	440363.
2	94564.02	0.157017	0.69263	60034.1	129094
3	38902.96	0.064596	0.75723	24697.6	53108.3
4	29305.62	0.0486	0.80589	18604.7	40006.5
5	27557.86	0.04575	0.85165	17495.2	37620.6



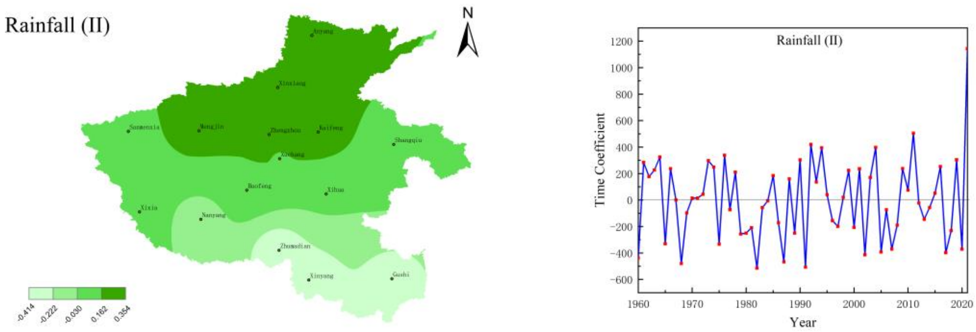


Figure 5.The First Mode Eof1 And The Second Mode Eof2 Of Precipitation In Henan Province During 1960-2021

In order to extract the typical features of precipitation in Henan Province, EOF decomposition was applied to conduct spatio-temporal decomposition of precipitation in Henan Province from 1960 to 2021, and five main precipitation modes were obtained, with a cumulative contribution rate of 85.16%. However, only the error ranges of the first two feature roots did not overlap through the North significance test. The contribution rates of the two modes are 53.56% and 15.70% respectively, and the cumulative contribution rate is 69.26%. It can be seen that the two modes can well explain the precipitation distribution types in Henan Province during 1960-2021.

According to the analysis of the spatial characteristics of the two modes, the precipitation types in Henan Province can be divided into four types. The contribution rate of precipitation EOF1 is 53.56%, which is the main distribution form of precipitation in Henan Province. The positive characteristic values indicate that the trend is highly consistent, which makes the precipitation in Henan Province show two types of rainy or less rainy throughout the whole year. The high value region appears in the southeast region, the southeast region is more volatile than the northwest region, the degree of change is high, and the central region is the transition region. The time series showed an increasing trend, showing an increasing trend of rainfall. The variance contribution rate of EOF2 mode 2 is 15.7%, and the eigenvalue is negative from north to south, showing a north-south reverse distribution pattern, which also shows another two types of precipitation in Henan province: more precipitation in the north, less precipitation in the south, or more precipitation in the south, less precipitation in the north. The increase trend in mode 2 of time series indicates that precipitation in the north has increased in recent 61 years, and precipitation in the south has decreased in the south.

5. Conclusion

(1) The interannual variation of temperature and precipitation in Henan Province shows an upward trend. The time of temperature rise is similar to that of global warming, with a warming amplitude of 0.23 ℃/10a. Precipitation shows fluctuating changes, with an overall increase of 4.88mm/10a in fluctuation. The sudden change in average temperature in Henan Province over the years occurred in the mid-1990s, with a more pronounced warming trend; The UF curve has many intersections with the UB curve within the confidence interval of the multi-year precipitation mutation test, mainly concentrated from 1973 to 1985. In terms of temperature, the time of temperature rise at each station is consistent with the overall MK temperature rise in the whole province, from the late 1980s to the early 1990s, with most sudden changes occurring around the late 1990s and the 2010s. The precipitation MK mutation test varies, and like the Z-value test, most of them fail the significance test.

(2)Four main modes were obtained through spatiotemporal decomposition of temperature in Henan Province from 1960 to 2021 using EOF. Only the first two modes had non overlapping error ranges and passed the North significance test. Mode one better reflects the main spatial and temporal characteristics of Henan Province, with high-value areas appearing in the Kaifeng area of Zhengzhou and gradually decreasing in the surrounding areas, and low value areas appearing in areas such as Sanmenxia, Xuchang, and Shangqiu. The temperature also shows an overall upward trend in the time series, consistent with global warming changes

(3)The typical characteristics of precipitation were analyzed using EOF to obtain five main modes of precipitation. Only the error ranges of the first two characteristic roots did not overlap and passed the North significance test. Precipitation EOF1 is the main distribution form of precipitation in Henan Province, with a highly consistent trend. The precipitation in Henan Province is characterized by two types of rainfall throughout the year: heavy or light. There is an increasing trend in the time series, indicating an increase in rainfall. The characteristic values of EOF2 mode 2 are positive in the north and negative in the south, showing a north-south reverse distribution pattern. This also indicates two other types of precipitation in Henan Province: more precipitation in the north and less precipitation in the south, or more precipitation in the south and less precipitation in the north. In time series mode 2, there is an increasing trend, indicating an increasing trend in precipitation in the north and a decreasing trend in precipitation in the south over the past 61 years.

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