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Climate Characteristics of Warm Season Precipitation in Eastern Asia in Recent 43 Years

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Abstract: *Based on the reanalysis data of ERA5 monthly average hourly precipitation for 43 years from 1979 to 2021 provided by the European Center for Medium-Range Weather Forecasts (ECMWF), temporal and spatial distribution and periodic change of warm season precipitation and extreme precipitation in recent 43 years are studied by the methods of the linear trend estimation, empirical orthogonal function (EOF), 9 points smoothing, Mann-Kendall mutation test, Morlet wavelet analysis. The climatic characteristics of warm season precipitation in the east of Asia are discussed in detail. The results show that the average warm season precipitation in the east of Asia is uneven, and the annual fluctuation is also large in the area with more annual precipitation. The annual average precipitation and interannual fluctuation are characterized by "high in coastal areas and low in inland areas". Expect for areas where precipitation is greatly affected by topography, the frequency of extreme precipitation decreases from coastal to inland and from low latitude to high latitude. The spatiotemporal variation characteristics of the warm season precipitation in the east of Asia reflect that the most areas of the warm season in the east of Asia had more precipitation before 2014, and the precipitation has shown a downward trend since 2015. There are three obvious mutation years (1982, 1986 and 1997) and four main precipitation cycles (4-5a, 8-9a, 13-14a and 27-28a).*

Keywords: *Warm season precipitation, Extreme precipitation, Spatiotemporal distributiion, EOF, Wavelet analysis*

1. Introduction

Eastern Asia is a typical monsoon climate region in the world, and is also a frequent area of natural disasters such as drought and flood. Due to the comprehensive influence of atmospheric circulation, sea as well as land position and other factors, the precipitation in east Asia has obvious spatial and seasonal differences. The sixth assessment report of IPCC [1] pointed out that under the background of global warming, the frequency and intensity of observed weather and climate extreme events have been increasing, and the number of people affected by extreme precipitation has increased significantly. The eastern part of Asia is high in the west and low in the east (Fig. 1), and faces the Pacific Ocean to the east. It is much affected by the southeast monsoon, and the precipitation intensity is large. The highest altitude is located in the Qinghai-Tibet Plateau, and the coastal areas are mostly plain areas with low terrain. In recent years, many scholars have carried out relevant research on the temporal and spatial characteristics of summer precipitation in Asia. Liu et al. carried out statistical analysis on the horizontal distribution characteristics of summer precipitation in Asia, and pointed out that there are three stable strong precipitation centers in Asia in summer, namely, the northern coast of the Bay of Bengal, the southern part of the South China Sea, and the equatorial Western Pacific Warm Pool [2]. Chen et al. discussed the characteristics of the average annual precipitation distribution of the warm season precipitation in Asia as well as its interannual and interdecadal changes characteristics [3]. The research showed that the warm season precipitation distribution in the Asian continent has significant regional variation characteristics, and the maximum precipitation occurs in the region affected by the summer monsoon. Zhang et al. studied the atmospheric teleconnection between Asia and the Pacific in summer, and analyzed the relationship between its seasonal evolution and the summer Asia-Pacific atmospheric circulation and precipitation in the Asian monsoon region [4]. It was found that there was a teleconnection phenomenon similar to the Asia-Pacific oscillation in the mid-latitude of Asia and the North Pacific in the diurnal disturbance temperature field in the upper troposphere from May to September. Ye et al. studied the interdecadal spatiotemporal variation relationship between summer precipitation in Eastern Asia and global sea surface temperature anomalies, and further learned that the coupling relationship between summer precipitation in East Asia and global sea surface temperature

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anomalies was affected by global warming, Pacific inter-decadal oscillation PDO, Atlantic inter-decadal oscillation AMO and North Pacific vortex oscillation NPGO respectively [5].

In recent years, there have been many studies on the spatial precipitation and its causes in some parts of Asia, but there are few studies on the warm season precipitation, extreme precipitation and periodic change laws in East Asia. Therefore, based on the spatial distribution of precipitation in Eastern Asia, the selection of extreme precipitation threshold in the warm season (March to September) in Eastern Asia is discussed, and the change cycle of average precipitation in the warm season in Eastern Asia is further discussed, so as to improve the level of climate prediction.

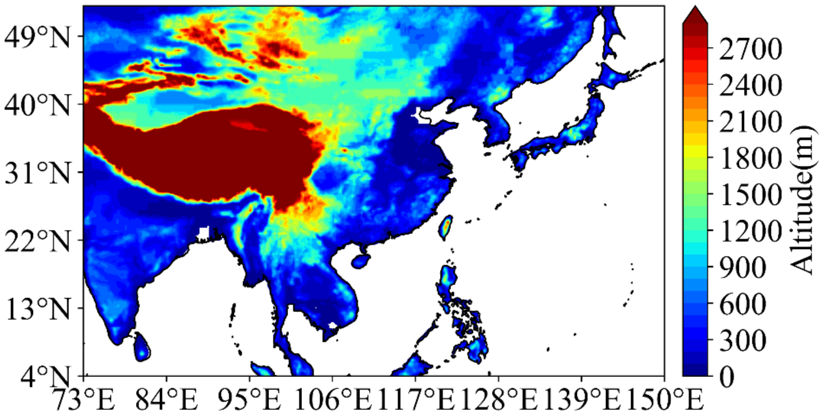

Figure 1: Topographic distribution in Eastern Asia

2. Data

In this study, the ERA5 hourly precipitation data is provided by the European Medium-Range Weather Forecast Center (ECMWF) including hourly precipitation data for 43 years from 1979 to 2021, with a horizontal spatial distribution rate of 0.25° × 0.25°. In addition, the 0.25 ° × 0.25° elevation data is provided by the National Oceanic and Atmospheric Administration (NOAA).

3. Spatial variation of warm season precipitation in Eastern Asia

3.1 Spatial distribution characteristics of warm season precipitation in East Asia

In order to study the spatial distribution characteristics of precipitation in the warm season (March to September) in Eastern Asia, the average annual average hourly precipitation is calculated from the monthly average hourly precipitation data of the warm season in Eastern Asia from 1979 to 2021 (Fig. 2a). The warm season precipitation in Eastern Asia has obvious sea-land distribution characteristics. The actual annual average hourly precipitation of the "rain pole" in the northeast of India can reach more than 40 mm, the annual average hourly precipitation of the west coast of Southeast Asia can reach more than 15 mm. The precipitation area in the eastern Philippines and southern Japan has an average annual hourly precipitation of more than 9mm. Southeast China is greatly affected by the southeast Pacific monsoon, with the annual maximum hourly precipitation of more than 12mm, while the hourly minimum annual precipitation is less than 1mm in the eastern and western continents of Asia and the eastern side of the Indian Peninsula. The difference between land and sea is obvious. Except for the area of Kilapenzi on the windward slope of the southern foot of the the Himalayas, the area of the east coast of the Indian Peninsula on the leeward slope and the area of northeast China blocked by tall mountains are greatly affected by topographic factors. The rest of the region is generally characterized by "high coastal area, low inland area".

In order to further discuss the fluctuation of the warm season precipitation in Eastern Asia, the standard deviation of the annual average hourly precipitation in the warm season in each region was calculated (Fig. 2b), and it was found that the spatial distribution characteristics of the standard deviation and the mean value had some similarities. At the same time, the average value of precipitation in some regions was large, and the annual fluctuation was also large. Especially in the precipitation areas of northeastern India, eastern Philippines and southern Japan, the interannual standard deviation can reach more than 2.4mm, while in

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the inland area of eastern and western Asia, the annual standard deviation is only about 0.03mm, which is also characterized by "high coastal and low inland".

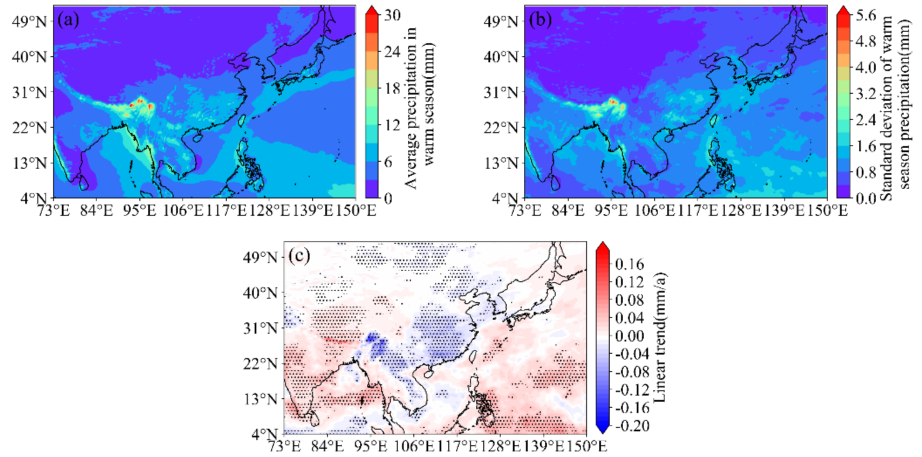

Figure 2: (a) Average warm season precipitation in eastern Asia (b) Standard deviation of interannual series (c) Spatial distribution characteristics of linear trend (the position of the black origin is indicated by α= 0.05 significance test)

In addition, in order to discuss the basic trend of the warm season precipitation change in Eastern Asia, the average annual hourly precipitation in each region in the warm season is linearly fitted to obtain its linear trend and significance (Fig. 2c). It can be seen that the linear trend in most regions of Eastern Asia is positive, while the linear trend in southeast China as well as the northern and eastern regions of the Indo-China Peninsula is negative. The western and northeastern parts of the Indian Peninsula, the southern part of the Bay of Bengal, the northern and eastern parts of the Indo-China Peninsula, the northern part of Mongolia, the southeastern part of China, the eastern and northeastern parts of the Philippine Islands passed α=0.05 significance test, and it shows that the annual hourly precipitation changes around 0.1mm, but there are still many regions that have not passed the test, so the overall change characteristics of precipitation in Eastern Asia from 1979 to 2021 are not completely linear.

3.2 Spatial distribution characteristics of extreme precipitation in Eastern Asia

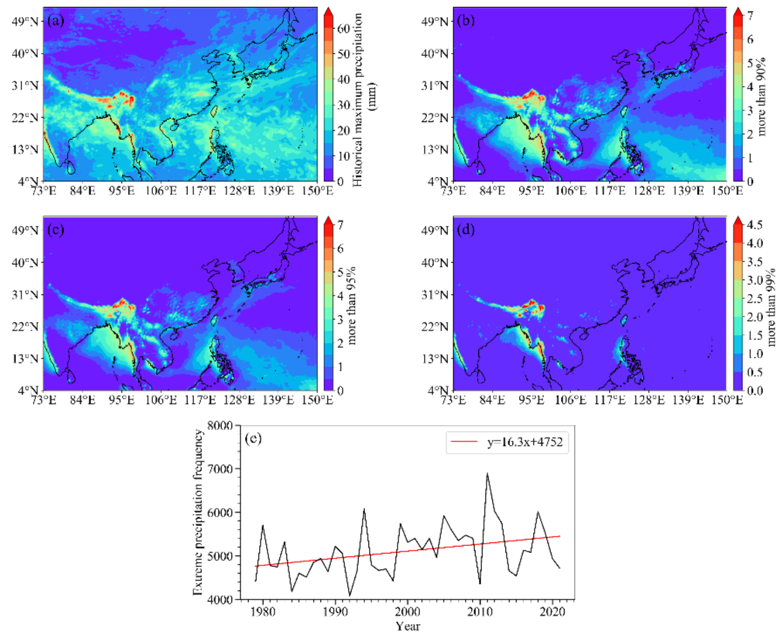

Figure 3: (a) The maximum monthly precipitation in the warm season in eastern Asia (b) monthly distribution of annual precipitation greater than 90% (c) monthly distribution of annual precipitation greater than 95% (d) monthly distribution of annual precipitation greater than 99% (e) monthly average extreme precipitation frequency

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Extreme precipitation is also a variable that needs to be paid attention to when studying precipitation climate characteristics. In order to understand the maximum hourly precipitation in various regions in the warm season in eastern Asia, the maximum monthly average precipitation in each region from 1979 to 2021 was calculated and the spatial distribution was drawn (Fig. 3a). It can be seen that the distribution of historical maximum precipitation is basically the same as that of climatic precipitation. The maximum hourly precipitation occurs in Kilapunzi, northeastern India, and the actual hourly precipitation can reach more than 90mm. The historical maximum hourly precipitation of the west coast of the Indian Peninsula, the west coast of the Indochina Peninsula and the west coast of the Philippine Islands also exceeded 45mm. However, the historical maximum hourly precipitation in the southeast of Kazakhstan and the northwest of China, which is located in the northwest inland, is less than 1mm. It can be seen that the precipitation difference between the coastal areas such as the west coast of the Pacific Ocean and the north coast of the Bay of Bengal and the northwest inland areas is large.

In order to discuss the precipitation intensity in eastern Asia, due to the wide scope of the study and the large difference of precipitation in the eastern and western regions, the hourly precipitation threshold in the discussion is taken from the 90th, 95th and 99th percentiles in the ascending order of annual average hourly precipitation in each region. The monthly number of hourly extreme precipitation in each region of eastern Asia during the warm season is counted (Fig. 3b-d). It can be seen from the figure that the distribution of hourly precipitation months greater than 90% and 95% is basically similar, while the number of hourly precipitation months greater than 99% is significantly reduced. It can be considered that it is more reasonable to define the hourly precipitation threshold during the warm season in eastern Asia in the 95th percentile. Therefore, the average monthly number of hourly extreme precipitation in eastern Asia is the largest in northeast India, with an average of 6-7 months per year in a total of 43 years from 1979 to 2021. The average annual number of extreme precipitation in the west coast of the Indo-China Peninsula and the Philippine Islands is more than 3 months, while the number of extreme precipitation in the eastern Philippines and southern Japan during the warm season is about 1-2 months. In general, the frequency of extreme precipitation in the warm season in eastern Asia is increasing year by year (Fig. 3e). Except for the areas where precipitation is greatly affected by the terrain, such as the eastern coast of the Indian Peninsula and the western coast of the Indo-China Peninsula, the frequency of precipitation in other areas is decreasing from coastal to inland as well as low latitude to high latitude.

4. Temporal and spatial evolution of warm season precipitation in Eastern Asia

4.1 EOF decomposition of warm season average precipitation in Eastern Asia

The study found that not all regions have a significant linear change trend, and the spatial distribution of average precipitation also has a large difference. In order to more accurately study the spatiotemporal variation characteristics of warm season precipitation in eastern Asia, the empirical orthogonal function (EOF) analysis was conducted on the anomaly field of warm season precipitation in eastern Asia [6], and the variance contributions of the first four modes were 51.89%, 7.47%, 4.55%, and 2.94%, respectively. The first mode explained that the variance contribution rate accounted for more than 50%, representing the main spatiotemporal variation characteristics, and the cumulative variance contribution rate of the first three modes was 63.91%. It basically reflects the main characteristics of the warm season precipitation spatial field in eastern Asia.

In order to make the results have a certain physical interpretation, on the basis of the EOF results of the average precipitation anomaly field in the warm season, the eigenvalues are standardized to obtain the standardized time coefficient. At the same time, the eigenvector is multiplied by the standard deviation of the eigenvalues to obtain a spatial type with the same dimension as the original field to measure the fluctuation degree of the water field of a certain mode decline with the standardized time coefficient. In addition, the 9 points smoothing of the time coefficient roughly represents the interannual change of the time coefficient. In the first mode (Fig. 4a, b), it can be seen that the spatial pattern is basically positive phase, except for a small number of regions such as eastern Kazakhstan, southeast China, the Pacific Ocean east of Japan, Sri Lanka and surrounding waters, which shows that the spatial pattern of most regions in eastern Asia fluctuates with the time coefficient in a phase state. Among them, the maximum value of positive phase appears in the west coast of Indo-China Peninsula, indicating that the main interannual variation feature of warm season precipitation in eastern Asia is the precipitation change in this region. According to the interannual variation of the first time coefficient 9 points, during the period 1995-2004, most regions in the warm season in eastern Asia had more precipitation, and the maximum value of the standardized time coefficient appeared in 1996, indicating that the precipitation distribution in that year was the most typical. After 2004, the precipitation in most regions showed a downward trend, and the normalized time coefficient after 2005 was negative, indicating that the precipitation in most regions was generally lower than the historical average level during this time period. The second mode spatial type (Fig. 4c, d) is mainly reflected in the antiphase changes between the Philippines and its eastern Pacific Ocean, southeast China and southern Japan. In combination with the smooth curve, take the southeast region of China with the maximum negative phase as an example. Because the feature vector of this region is negative phase, the smaller the time coefficient, the more precipitation in the southeast region of China, and vice versa. Before 2007, there was more precipitation in southeast China, but it decreased after 2007. The third mode spatial type (Fig. 4e, f) shows an obvious "positive negative" phase distribution in the north of the Indian Peninsula, the north of Indochina Peninsula, the west of Japan and the south of the Indian Peninsula, the south of Indochina Peninsula, and the Pacific Ocean. Combined with the time coefficient, taking the positive phase area as an example, the precipitation showed an increasing trend from the end of the 1980s, and decreased by the end of the 20th century, while the results in the negative phase area were opposite. It is generally shown that during the period from the 1980s to the end of the 20th century, the precipitation in the land area except the Indo-China Peninsula was greater than that in the sea area.

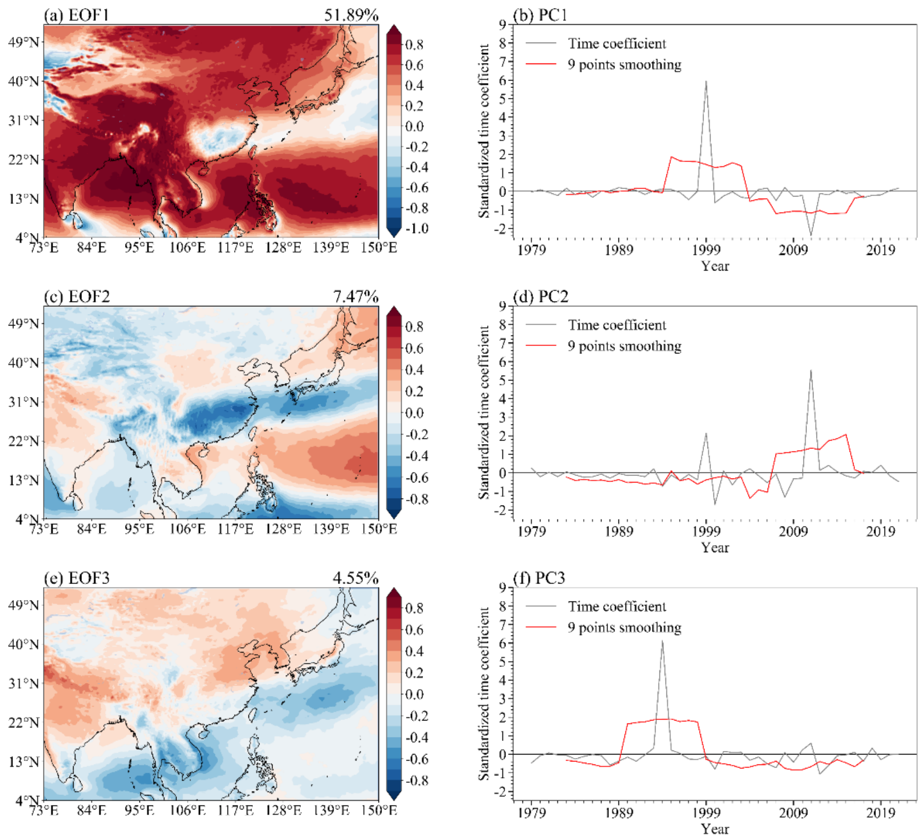

Figure 4: The spatial distribution and corresponding time coefficients of the first three EOF modes of warm season precipitation in Eastern Asia

4.2 Catastrophe test of warm season mean precipitation in Eastern Asia

In order to further discuss the trend and mutation of the average precipitation in the warm season in eastern Asia, the M-K mutation test is performed on the time coefficients of the first three modes of EOF in the previous section to calculate the UF and UB values [7], observe the location of the mutation point, and combine $\alpha= 0.05$ to infer the year of mutation. The UB statistic of the first mode time coefficient was positive in the late 1990s and had an upward trend, and it broke through the significant threshold in 2017, indicating that the precipitation increased significantly during this period, of which 1982, 1986 and 1997 were the years with significant abrupt changes in precipitation (Fig. 5a). The time coefficient of the second mode had no significant trend and significant mutation before 2005 (Fig. 5b). During 2005-2011, UB statistics declined significantly and intersected with UF statistics in 2010, indicating that the precipitation during this period showed a downward trend, of which the 2010 was the year of abrupt precipitation change. The UB statistics of the time coefficient of the third mode are all positive and have an upward

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trend after 1985, and broke through the significant threshold in 2012, indicating that since 1985, the precipitation has shown an increasing trend, of which 1985, 1992, 1997 and 2002 are the years with obvious abrupt changes in precipitation (Fig. 5c).

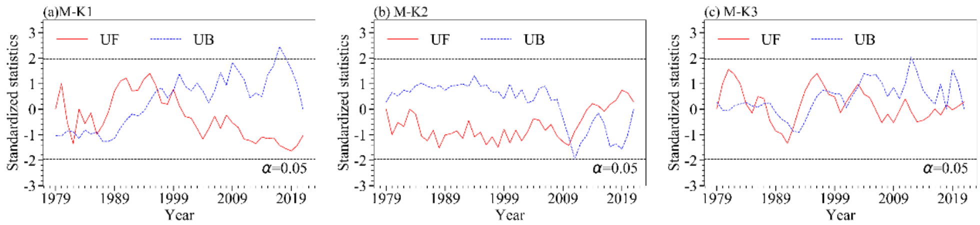

Figure 5: M-K catastrophe test of the first three modal time coefficients of warm season precipitation EOF in Eastern Asia

4.3 Periodic variation of warm season mean precipitation in Eastern Asia

In order to further discuss the change period of the average precipitation in the warm season in eastern Asia, Morlet wavelet transform is applied to the three modal normalized time coefficients obtained before the EOF in section 3.1 [8], and the wavelet coefficient diagram and variance diagram are drawn. According to the wavelet results of the first mode time coefficient (Fig. 6a, b), there are four main precipitation cycles, namely 4-5a, 8-9a, 13-14a and 27-28a, for the average precipitation in the warm season in eastern Asia. In 1995-2009, the first three precipitation cycles were more obvious, while the 27-28a cycle was more obvious before 2018. The second mode (Fig. 6c, d) has a main precipitation cycle of 12-13 years, which is more obvious after 1999. The third mode (Fig. 6e, f) has multiple time scale periodic changes, in which 14-15a and 26-27a are the main precipitation cycles, and the changes are more obvious before 2005 and 2015 respectively.

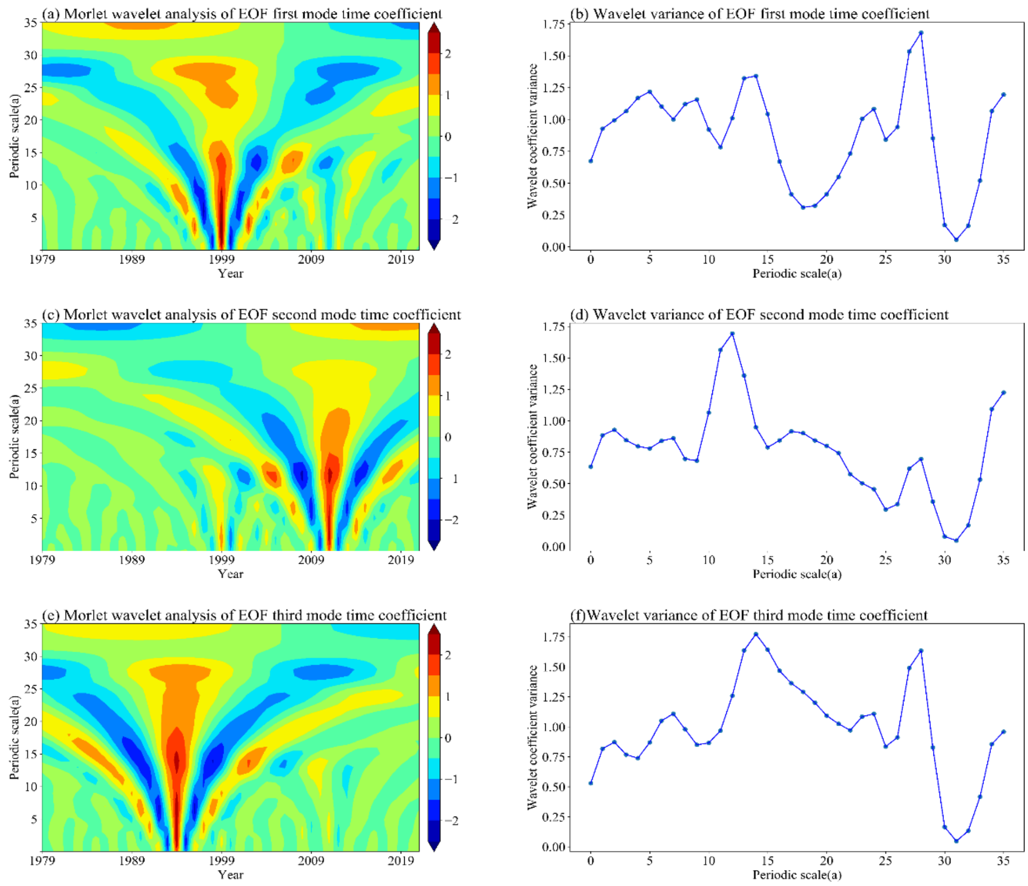

Figure 6: Morlet wavelet coefficients and variance diagrams of the first three modes of EOF

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5. Conclusions

Based on the precipitation data of 43 years from March to September in eastern Asia from 1979 to 2021, the spatial distribution characteristics and periodic changes of annual average precipitation and extreme precipitation in the warm season in eastern Asia are analyzed by using the methods of linear trend, EOF analysis, M-K mutation test and Morlet wavelet analysis.

The main conclusions are as follows. 1.The spatial distribution of annual precipitation in the warm season in the rest of eastern Asia is generally characterized by "high in the coastal area and low in the inland area". 2.The precipitation frequency of extreme precipitation in warm season in eastern Asia is decreasing from coastal to inland and from low latitude to high latitude. 3.The first mode of the average warm season precipitation in eastern Asia reflects that the spatial pattern of most regions in eastern Asia fluctuates with the time coefficient in a phase manner. The second mode space type reflects the antiphase change between different regions. The third mode spatial pattern reflects the obvious "positive negative" phase distribution of land and sea. 4.It is found that the first mode precipitation has four main precipitation cycles, namely 4-5a, 8-9a, 13-14a and 27-28a. The second mode has a main precipitation period of 12-13 years. The third mode has multiple time scale periodic changes, in which 14-15a and 26-27a are the main precipitation periods.

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