Decadal Variability of Extreme Precipitation Days over Northwest China from 1963 to 2012

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ABSTRACT

Daily precipitation data from 153 meteorological stations over Northwest China during summer from 1963 to 2012 were selected to analyze the spatiotemporal distribution of extreme summer precipitation frequency. The results show that the extreme precipitation frequency was regional dependent. Southern Gansu, northern Qinghai, and southern Shaanxi provinces exhibited a high extreme precipitation frequency and were prone to abrupt changes in the frequency. Northwest China was further divided into three sub-regions (northern, central, and southern) based on cluster analysis of the 50-yr extreme precipitation frequency series for each meteorological station. The extreme precipitation frequency changes were manifested in the northern region during the late 1970s and in the central region from the end of the 1980s to the 1990s. The southern region fluctuated on a timescale of quasi-10 yr. This study also explored the mechanism of changes in extreme precipitation frequency. The results demonstrate that stratification stability, atmospheric water vapor content, and upward motion all affected the changes in extreme precipitation frequency.

Key words: extreme precipitation frequency, Northwest China, stratification stability, water vapor content, atmospheric upward motion

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1. Introduction

As a result of global warming, the temperature in China has exhibited an increasing trend since the 20th century. The frequency of extreme weather and climate events has also increased and thus drawn the attention of meteorological researchers (Zou et al., 2009). Studies show that extreme weather events have caused serious weather and climate disasters (Johanna and Jenny, 2002; Chen et al., 2012; Wang et al., 2012).

The classification of extreme weather and climate events has spurred intensive debates. Working Group I of the Intergovernmental Panel on Climate Change (IPCC) suggested that extreme weather and climate events can be classified based on evaluation of the following four elements: (1) maximum and minimum temperature, diurnal temperature range, hot and cold period length, and heat index; (2) precipitation intensity and frequency, including drought and wet periods; (3) tropical cyclones (including cyclone intensity, track, frequency, location, maximum wind speed, probable maximum intensity, and sea surface temperature) and extratropical cyclones (including storm track, sea-level pressure gradient, wind, water level,

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storm surge, and wave height); and (4) thunderstorms and other microscale weather, including tornadoes and related phenomena, such as hail, lightning, dust devil, waterspout, downpour, snowstorm, and cloud surge.

Based on analysis of average precipitation in the 20th century, Iwashima and Yamamoto (1993), Tosnis (1996), and Fu et al. (2006) found that the frequency and intensity of extreme precipitation events have significantly changed worldwide. During the 20th century, precipitation increased by 5%–10%, and the frequency of extreme precipitation events increased by an average of 2%–4% over continents in the mid-high latitudes of the Northern Hemisphere (Milly et al., 2002). The results of numerical modeling show that the regional climate condition demonstrates a polarizing trend under doubled concentrations of greenhouse gases (Zwiers and Khrin, 1998; Bell et al., 2004; Pal et al., 2004; Min and Qian, 2008).

Zhai et al. (2005) discovered that the frequency of extreme precipitation (more than 95% of the daily precipitation sequence) events has exhibited an increasing trend over Northwest China in recent years. The number of extreme precipitation events has also increased by 100%. Yang et al. (2007) found a significant difference between the frequency of extreme precipitation and spatial distribution of rainfall during the flood season in Northwest China. Chen et al. (2013) indicated that Northwest China witnessed fluctuations in precipitation in the last 40 years, and different anomaly regions showed different trends with obvious periodic, annual, and decadal variations. Shi et al. (2002) showed that precipitation in Northwest China has exhibited an increasing trend over the past century. They also found that the increased frequency of extreme weather events can be associated with climate transformation from wet to dry. Chen et al. (2012) and Zhang et al. (2012) emphasized that the frequency of extreme weather events and the degree of damage resulting from these events will continue to increase.

Northwest China is located in arid and semi-arid regions, under certain influences of terrain and other geographic conditions. Extreme precipitation events pose a serious threat to the ecological environment of Northwest China and can seriously restrict the development of the local economy (Zhang et al., 2012; Zhang and Dai, 2012; Chen et al., 2013). Studying the spatiotemporal distribution of extreme precipitation events in Northwest China is important to meteorological disaster prevention and mitigation. This study discusses the spatiotemporal distribution of extreme precipitation in Northwest China during summer. It also aims to show the regularity and characteristics of extreme precipitation events in Northwest China over the past 50 years.

2. Data and methods

The data used in this study were gathered from the "China's ground, high-altitude, and radiation station basic information list" released by the data service section of the National Meteorological Information Center (NMIC) of China. Precipitation data from 177 stations in 5 northwestern provinces/regions (Gansu Province, Ningxia Region, Qinghai Province, Shaanxi Province, and Xinjiang Region) from 1961 to 2012 were selected. These data include those from 1961 to 2010 of the "1951–2010 monthly data of China national ground station data corrected file (A0/A1/A) basic dataset" compiled by the ground meteorological data archive construction project. Data from January 2011 to August 2012 were based on the monthly report submitted by each province/region to the NMIC, and data from September 2012 to October 2012 were based on real-time records of the NMIC.

Daily precipitation intensity was categorized into the following five grades: sprinkle rain ($\leqslant$ 10 mm day^{-1}), moderate rain (10–25 mm day^{-1}), heavy rain (25–50 mm day^{-1}), torrential rain (50–100 mm day^{-1}), and downpour ($\geqslant$ 100 mm day^{-1}). In this study, extreme heavy precipitation event days were defined as the days with rainfall of more than 25 mm day^{-1}. Stations with considerable missing data on the extreme precipitation events were excluded. Finally, 153 stations were selected.

Based on multi-stage fitting, we conducted nine-year sliding-moving t-test, wavelet analysis, Mann–Kendall (M–K) test, and analysis on spatiotemporal variations of the extreme precipitation frequency. Northwest China was further divided into three subregions with clustering analysis on the extreme precipitation frequency time series at each of the 153 stations for 1963–2012.

3. Spatial distribution of extreme precipitation event frequency

Figure 1 shows the spatial distribution of the frequency and variance of extreme precipitation events during summer in Northwest China over the past 50 years. A high frequency of summer extreme precipitation was observed in the south of Qinghai to Shaanxi, where the average annual extreme precipitation days reached 12 days (Fig. 1a). The maximum area was located in southern Qinghai, Gansu, and southern Shaanxi, where the average annual extreme precipitation days reached 16 days. The average annual extreme precipitation days in the eastern region of the Tanggula Mountains reached 20 days, a result indicating that this area was most prone to heavy precipitation. Meanwhile, the regions with the lowest frequency were located in the Tarim and Junggar basins in Xinjiang (north of the Kunlun Mountains). Extreme precipitation days were fewer in the Tarim basin (< 4 days) than in other areas. This phenomenon is associated with drought. The extreme precipitation frequency in the central region of Qinghai showed the largest meridional gradient. The average annual extreme precipitation frequency in northern Qinghai was less than 8 days, whereas that in the southern region reached 20 days.

The large standard deviation of heavy rainfall days during summer was nearly collocated with the large frequency of annual extreme precipitation days (Fig. 1b). Large standard deviation of more than 3.5 days yr^{-1} occurred over southern Qinghai and the Hetao region. The standard deviation over the eastern Tangula Mountain in southern Qinghai reached 6 days yr^{-1}, indicating a large difference in the interannual variability of extreme precipitation frequency. Similar to the distribution of extreme precipitation frequency, a small standard deviation occurred in Xinjiang Region (< 2 days yr^{-1}).

To study the spatial variation of heavy rainfall event (HRE) frequency, the annual extreme precipitation frequency anomaly from 1961 to 2012 was decomposed by empirical orthogonal function (EOF) analysis. The variances of the first, second, and third feature vector fields were 17.4%, 14.9%, and 7.3% of the total variance, respectively.

The positive load of the first eigenvector field (Fig. 2a) covered most of the study area and thus reflected the consistency of extreme summer precipitation frequency in Northwest China. The center of a large load value was located in southern Qinghai and southern Shaanxi, indicating the largest change rate of extreme precipitation frequency in these areas. The corresponding temporal coefficient exhibited mutations (Fig. 2b) around 1979. The early period was mainly negative, whereas the late period was mostly positive. This finding validates the low frequency of extreme precipitation in Northwest China during the early period and the high frequency during the late period. Figure 2b also shows the decadal variabilities with negative values during the 1960s–1970s and 1995–2004, and positive values during 1979–1995 and

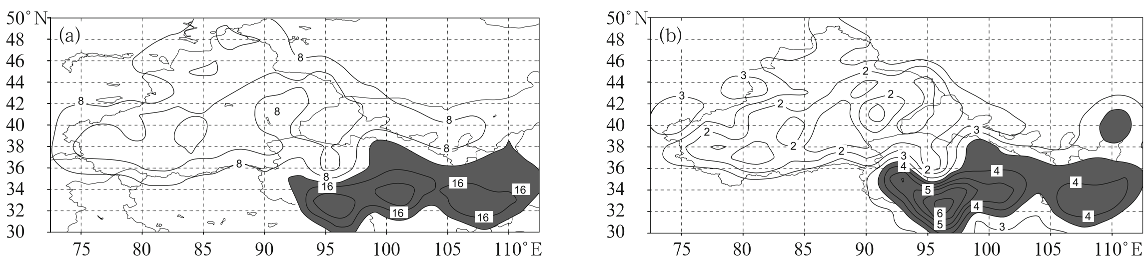

Fig. 1. Geographical distributions of (a) the annual mean number of heavy rainfall days (over 12 within the shaded area) and (b) the corresponding standard deviation (day yr^{-1}; over 4 within the shaded area) from 1961 to 2012.

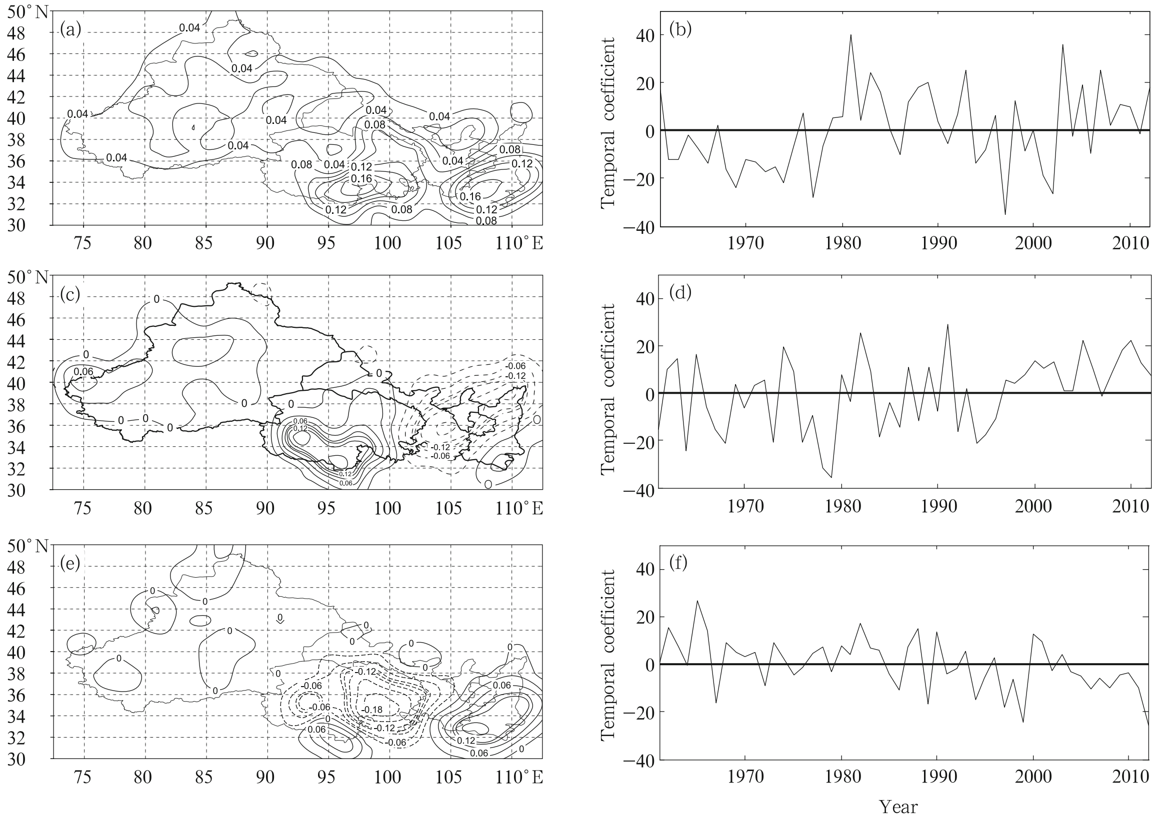

Fig. 2. First leading mode of the EOF analysis on the leading 20 EOFs of the normalized HRE (heavy rainfall event) frequency from 1961 to 2012 in Northwest China. (a, c, e) The first, second, and third eigenvector fields, and (b, d, f) the corresponding temporal coefficients.

2004–2012.

The second eigenvector field (Fig. 2c) was distinguished from the first eigenvector field in spatial distribution. The second eigenvector was positive in southern Qinghai, and the largest load-capacity area was located in the north of the Tangula Mountain. Meanwhile, the value was negative in southern Gansu, Ningxia, and Shaanxi. The largest load-value area was located in southern Gansu, Ningxia, and northern Shaanxi. Therefore, the changed characteristic in southern Qinghai was opposite to those of southern Gansu, Ningxia, and Shaanxi. The distribution of extreme precipitation frequency from Shaanxi to Qinghai had a west-high and east-low feature or vice versa. The corresponding time coefficient (Fig. 2d) was almost entirely negative before 1997 and positive after 1997. This result indicates that the extreme precipitation frequency was low during the early stage in Qinghai, but it was high in the Shaanxi-Gansu-Ningxia area. The frequency was reversed during the late period. Figure 2d shows an increasing trend from large negative values during the 1960s–1970s to positive values after 2000.

In the third characteristic vector field (Fig. 2e), the high value located in eastern Qinghai, southern Gansu, and Shaanxi was positive; the large load capacity was located in southern Shaanxi. Therefore, the tendency of Qinghai was opposite that of the southern Gansu-Shaanxi area. The east–west difference in these two areas was the third space exception type. The corresponding time coefficient (Fig. 2f) was almost entirely positive before 1995 and negative after 1995. This result indicates that the extreme precipitation frequency during the early stage was low in Qinghai but high in Shaanxi, whereas that of the late period was opposite. Figure 2f depicts a decreasing trend from positive values during the 1960s–1980s to negative values during the 1990s–2000s.

4. Time variation of extreme precipitation frequency

4.1 The time series of extreme precipitation frequency

Figure 3 shows the time series of extreme precipitation frequency, its fifth-order polynomial fitting, and decadal values in northwestern provinces/regions. Extreme precipitation frequency generally exhibited an increasing trend in Northwest China. Gansu and Ningxia demonstrated a slightly downward trend. By contrast, Qinghai and Xinjiang showed an upward trend, particularly in Qinghai, where the average number of HRE days from 2003 to 2012 increased by approximately 1.5 days compared with that from 1963 to 1972. Shaanxi did not exhibit any notable trend.

Mutation testing of the time series in Northwest China by using the M–K method (Huang et al., 2012) showed that a mutation in extreme precipitation frequency occurred in 1979 (Fig. 4). UF tracts were

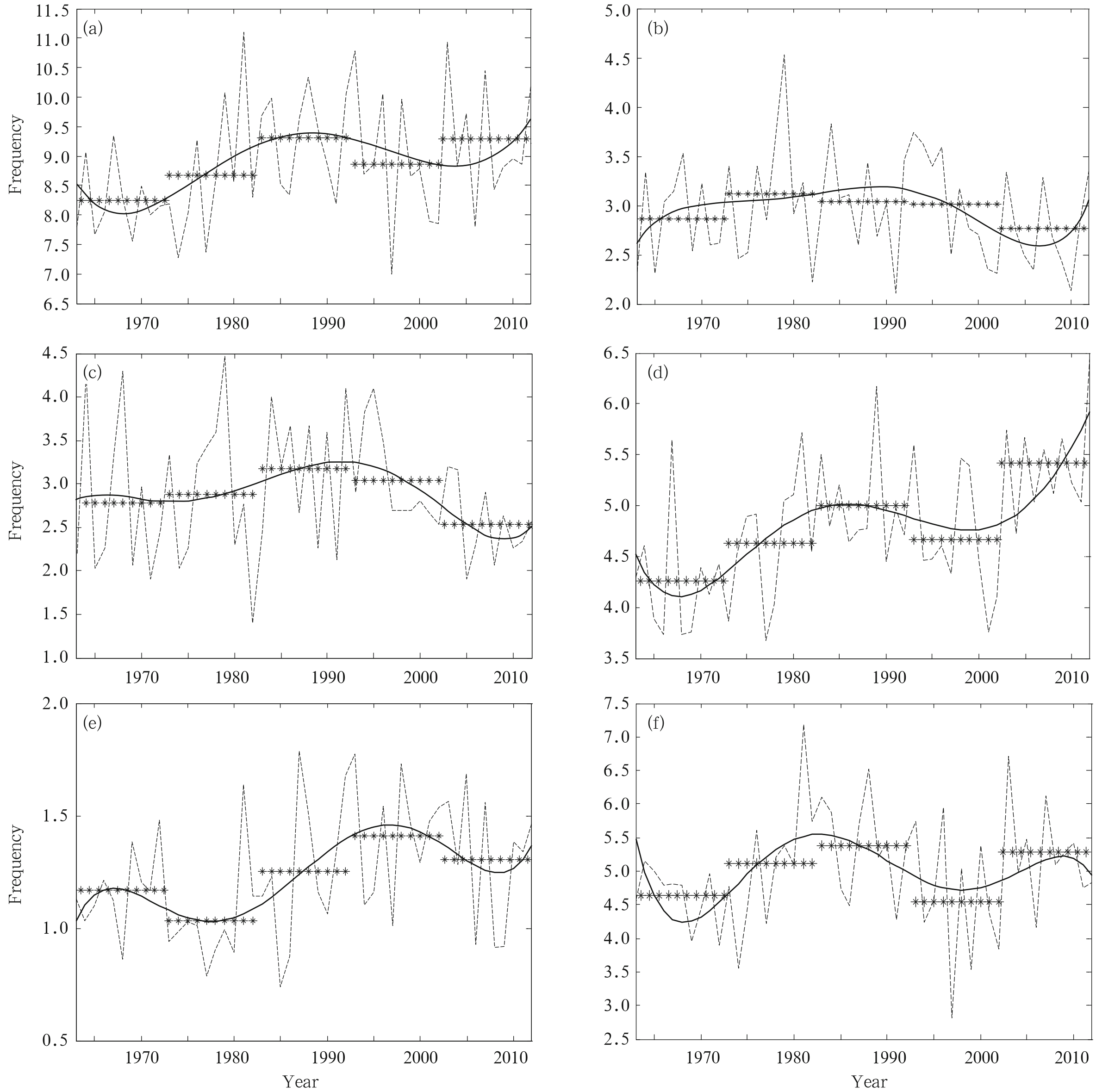

Fig. 3. HRE frequency time series (dashed line) and its fifth-order polynomial (solid line) and average for each decade (asterisk) for (a) Northwest China, (b) Gansu Province, (c) Ningxia Region, (d) Qinghai Province, (e) Xinjiang Region, and (f) Shaanxi Province from 1963 to 2012 (unit: number of occurrences per year per station).

mainly negative before 1979, but these became positive after 1979. The results show that the extreme precipitation frequency in Northwest China increased after 1979. The analysis result exceeded the critical value after 1985, indicating that the extreme precipitation frequency exhibited a significant upward trend with the fastest rising period during the 1990s. The intersection point of UF and UB (UF and UB stand for the forward sequential statistic and backward sequential statistic of M-K test), i.e., the frequency mutation point located within the line of the significant level confidence (±1.96), appeared from 1978 to 1979. These findings suggest that extreme precipitation frequency exhibited mutations from 1978 to 1979 in Northwest China, and an increasing trend was recorded in the late period, particularly in recent years.

To verify the accuracy of the mutation points, we conducted a 9-yr sliding test (Cheng and Wang, 2004) on the extreme precipitation frequency for each province/region in Northwest China. Table 1 shows a mutation in 1979, which is similar to that found in the M–K analysis (Fig. 4). Considerable mutations occurred around 1977 and from 1994 to 2002. A large mutation occurred during the 1970s in Qinghai and Xinjiang. The mutation time span in Shaanxi was generally similar, but the mutation intensity was less than those in Qinghai and Xinjiang, and the frequency did not exhibit any trend. The frequencies barely changed in Gansu and Ningxia during the early period, and mutations mainly occurred after the 1990s.

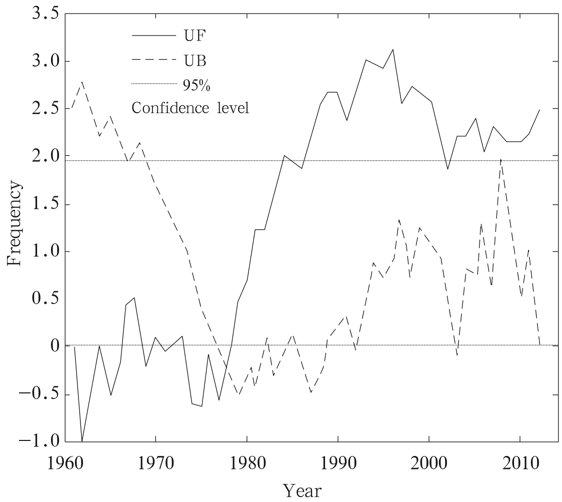

Fig. 4. Temporal variation in the frequency of HREs in Northwest China through M–K analysis.

Table 1. Abrupt change (mutation) years of heavy rainfall events in Northwest China from 1963 to 2012 on the basis of a 9-yr sliding-moving t-test

Region/Province	Mutation frequency of extreme precipitation
Northwest China	1971*, 1979**
Gansu	1998**, 2000**
Ningxia	1996*, 1998*, 2000**, 2004**
Qinghai	1971**, 1974*, 1978**, 1994*, 2002**
Xinjiang	1972**, 1986*
Shaanxi	1967**, 1989*, 1994*, 2002*

Note: * and ** denote the 90% and 95% confidence levels, respectively.

4.2 Wavelet analysis

Wavelet analysis was performed to elucidate the mutation of extreme precipitation frequency in northwestern provinces/regions over the past 50 years (Niu et al., 2004; Shao et al., 2006; Jiang et al., 2009). The result of the wavelet analysis shows a 2-yr cyclical swing of extreme precipitation frequency in Northwest China (Fig. 5a). On a timescale of 10 yr or more, a noticeable mutation occurred in 1979. This mutation value was negative during the early stage and positive during the late stage. The maximum value was observed from 1985 to 1995, indicating that the frequency rapidly increased after the mutation point. The maximum frequency occurred during the 1990s, a finding that is consistent with previous analyses (Niu et al., 2004; Shao et al., 2006; Jiang et al., 2009).

A 2–4-yr cyclical swing occurred in Gansu Province (Fig. 5b). On the decadal scale, the value was negative before 1975 and after 1995, and it was positive from 1975 to 1995. Mutation occurred in 1997. This result indicates that the extreme precipitation frequency from 1975 to 1995 was high, whereas the lowest frequency occurred in Gansu Province from 2000 to 2010. A 2–4-yr cyclical swing was also observed in Ningxia Region (Fig. 5c). However, on a 4–14-yr time scale, the frequency was low during the early and late years, but it was high in between. The mutation point occurred in 2000.

A low-high-low-high trend was observed in Qinghai Province (Fig. 5d). On the 6–8-yr timescale, the value was low in 1970 and 2000, but it was high around

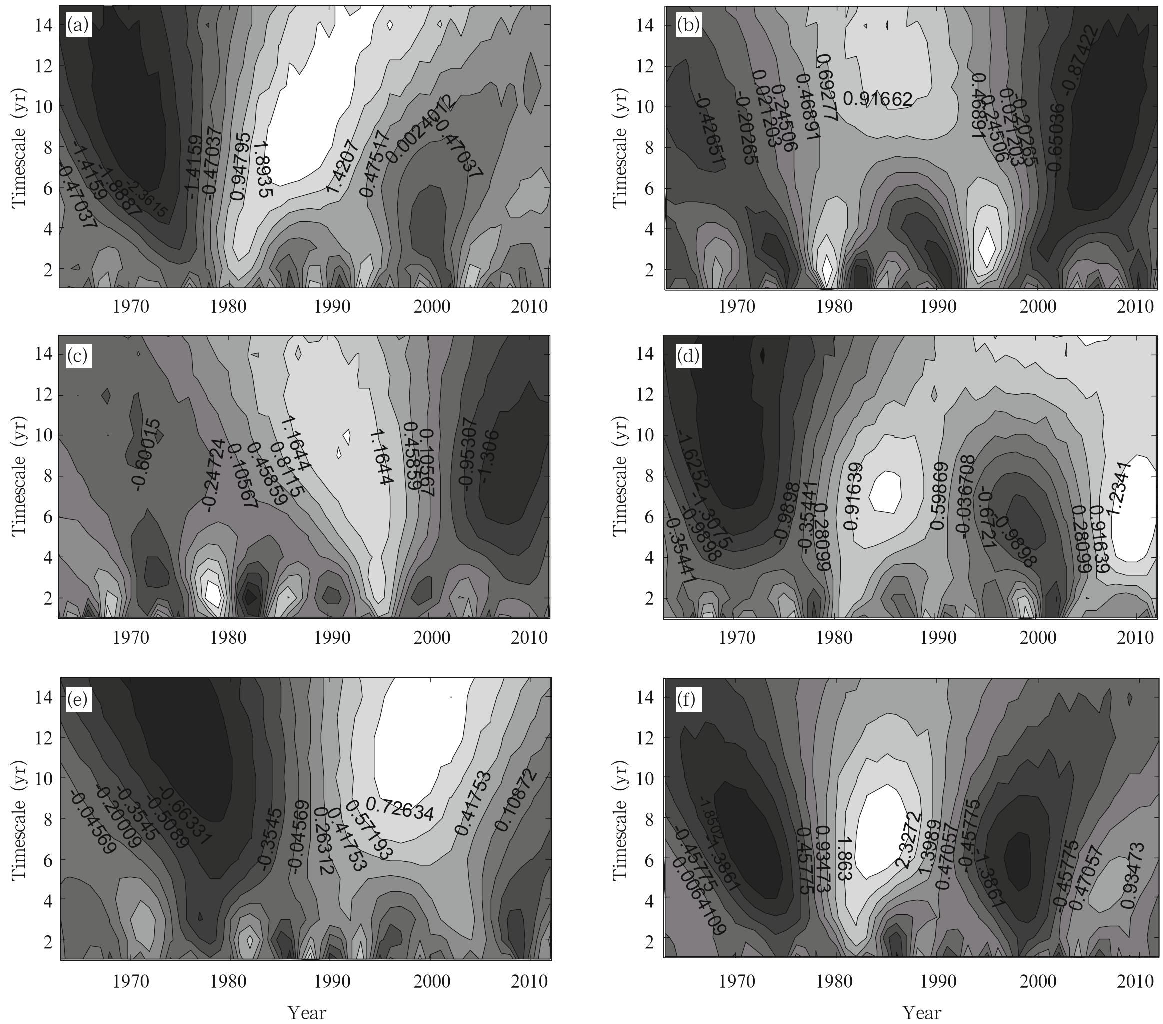

Fig. 5. Wavelet spectra of heavy rainfall days in Northwest China and in each province/region from 1963 to 2012 with Mexican hat wavelet analysis. (a) Northwest China, (b) Gansu Province, (c) Ningxia Region, (d) Qinghai Province, (e) Xinjiang Region, and (f) Shaanxi Province. The dark black and gray areas denote negative and positive values, respectively.

1985 and 2010. The interdecadal timescale generally exhibited an increasing trend. A noticeable mutation occurred in 1979. A 2–4-yr cyclical swing occurred in Xinjiang Region. The minimum value occurred in 1975, whereas the maximum value occurred in 2000. Meanwhile, a 3–10-yr cyclical swing was observed in Shaanxi Province (Fig. 5f). Two maximum and minimum values were found. The minimum values occurred in 1975 and 2000, whereas the maximum values occurred in 1986 and 2008. A significant mutation occurred in 1979, 1990, and 2002 (Fig. 5f).

4.3 Decadal variability

The differences in the 10-yr mean extreme precipitation frequency between two adjacent decades from 1963 to 2012 were calculated to analyze the decadal variation of extreme precipitation frequency in Northwest China (Fig. 6). In northern Qinghai, the central and western Gansu and eastern Xinjiang showed a similar horizontal distribution, but they exhibited less intensities compared with those in southern Qinghai, Shaanxi, and southern Gansu. This phenomenon

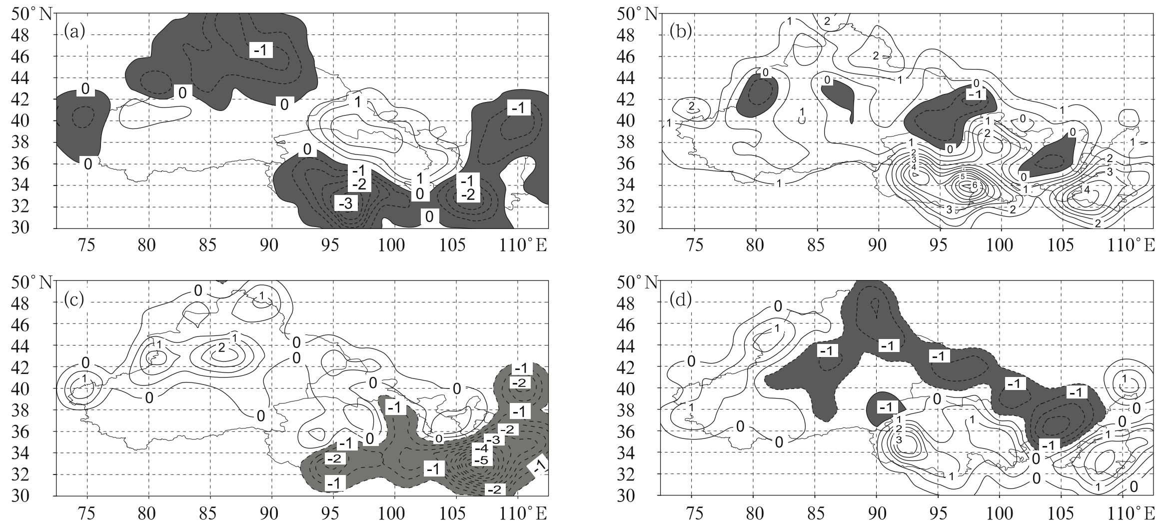

Fig. 6. Horizontal distributions of the differences in 10-yr mean heavy rainfall days (day yr^{-1}) between (a) the 1970s and 1960s, (b) the 1980s and 1970s, (c) the 1990s and 1980s, and (d) the 2000s and 1990s. Negative areas are shaded.

may be related to the mountainous topography of southern Qinghai, Shaanxi, and southern Gansu, which favors the development of cyclones. By contrast, northern Qinghai, central and western Gansu, and eastern Xinjiang are characterized by northerly-westerly winds, which favor the development of anticyclones.

In the present study, Northwest China was further divided according to the frequency trend characteristics of extreme precipitation (Fig. 7). We used cluster analysis to the time series of extreme precipitation frequency to study the characteristics of the region (see also Cheng et al., 1998, 2001). Northwest China can be divided into three regions, namely, Xinjiang to the north of Gansu and west of the Tarim basin (Zone 1; Fig. 7a), west of Qinghai and the Shaanxi-Gansu-Ningxia area (Zone 2; Fig. 7c), and southern Qinghai to the southern Shaanxi and Hexi Corridor area (Zone 3; Fig. 7e).

Wavelet analysis shows that Zone 1 (Fig. 7b) underwent a mutation during the late 1980s and around 2000, and the extreme precipitation frequency significantly increased between these two mutation points. The minimum frequency appeared in 1973, whereas the maximum one occurred in 1998. Zone 2 (Fig. 7d) exhibited a mutation from 1978 to 1979 on the decadal timescale. The precipitation in Zone 2 significantly increased compared with that in Zone 1. Zone 3 (Fig. 7f) exhibited periodic oscillation trends on the 3–15-yr timescale. One maximum (in 1985) and two minimum (around 1970 and 1999) frequencies occurred over the past 50 years. The mutations occurred in 1978 and 1992.

5. Factors influencing the extreme precipitation events

5.1 Stratification stability

The two important factors that affect precipitation development are moisture and thermal stability. Chen et al. (2012) and Zhang et al. (2012) introduced an index (K) to denote these two factors, which can be expressed as

$$K = (T_{850} - T_{500}) + T_{\mathrm{d}850} - (T_{700} - T_{\mathrm{d}700}), \qquad (1)$$

where T is the air temperature and T_{d} is the dewpoint temperature. On the right side of Eq. (1), the first term represents the temperature-lapse rate in the lower troposphere, the second term denotes the moisture in the lower troposphere, and the third term indicates the atmospheric saturation and thickness of wet air in the mid troposphere. The increase in the possibility of extreme precipitation can be associated with the increase in K.

The K index of Northwest China (Fig. 8a) and the individual provinces/regions (Figs. 8b–f) generally exhibited an increasing trend before the 1990s, which favored the development of extreme precipitation (see Fig. 3). The K index in Gansu and Ningxia showed decadal tendencies similar to those of the extreme precipitation frequency in the same region. The K index in Qinghai mainly presented an increasing trend, except for a brief decline during the 1980s. In Xinjiang, the similarity between the K index and extreme precipitation variation trends was low. The possible reasons might be the dry air, small precipitable water, and low atmospheric humidity significantly affecting the extreme precipitation in Xinjiang.

Figure 9 shows the mean difference of the K index between each decade from 1963 to 2012. The decadal changes of K over Northwest China were mainly positive between the 1970s and 1960s (Fig. 9a) and thus favored extreme precipitation. The negative decadal changes of K were mainly located in southern Qinghai. The interdecadal average difference of the K exponential was fundamentally similar to that of extreme precipitation. Therefore, the change in extreme precipitation frequency was significantly related to the K index from the 1960s to the 1970s.

Between the 1980s and 1970s (Fig. 9b), the mean difference of K in Qinghai and most areas of Xinjiang was negative, and the area with the minimum value was located in northern Xinjiang. Positive values were observed in the other regions. The area with the maximum value was in Ningxia and northern Xinjiang. During this period, the extreme precipitation frequency (Fig. 6b) was generally increasing, except for a slight decrease in a few areas in central Xinjiang and in northern and southern Gansu. The frequency in the other regions, particularly in southern Qinghai, Gansu, and southern Shaanxi, significantly increased. Therefore, during this period in western Qinghai, southern Gansu, Ningxia, and Shaanxi, the extreme precipitation frequency was significantly

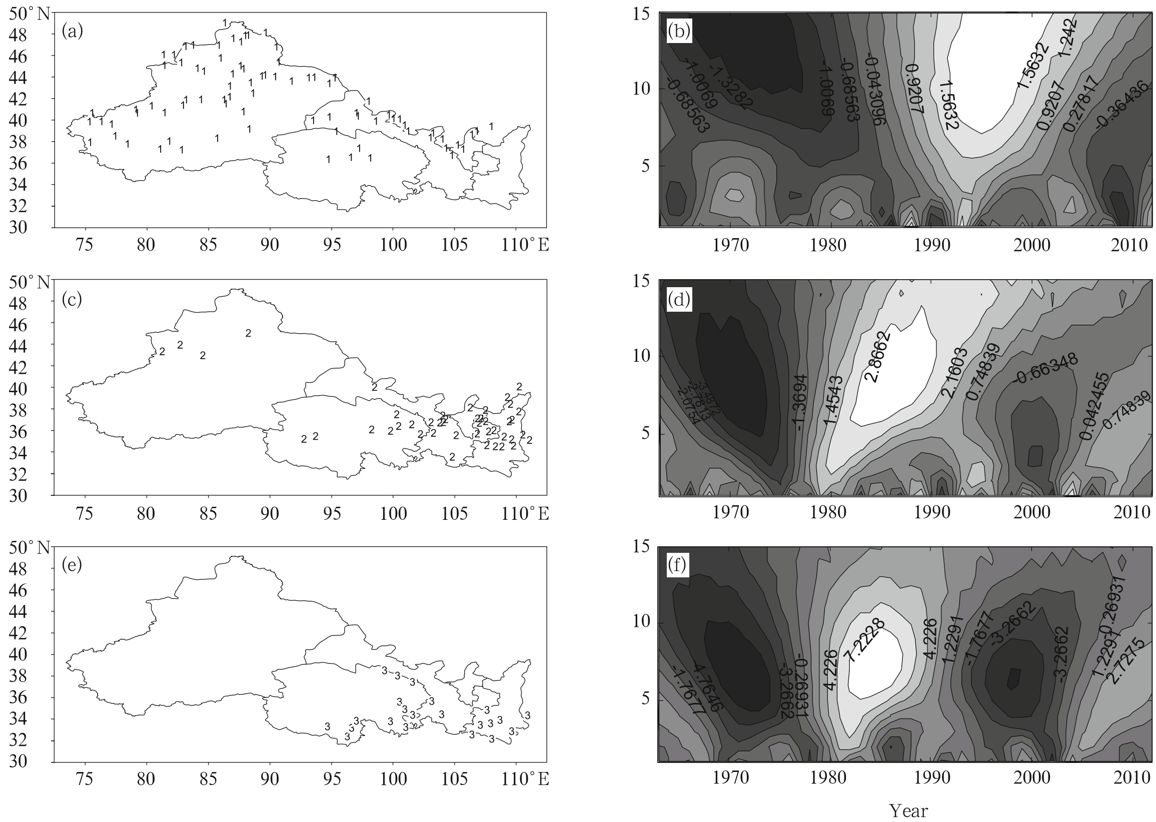

Fig. 7. Zones divided by cluster analysis of the time series of extreme precipitation frequency of each station in Northwest China (a, c, e) and their wavelet analysis (b, d, f).

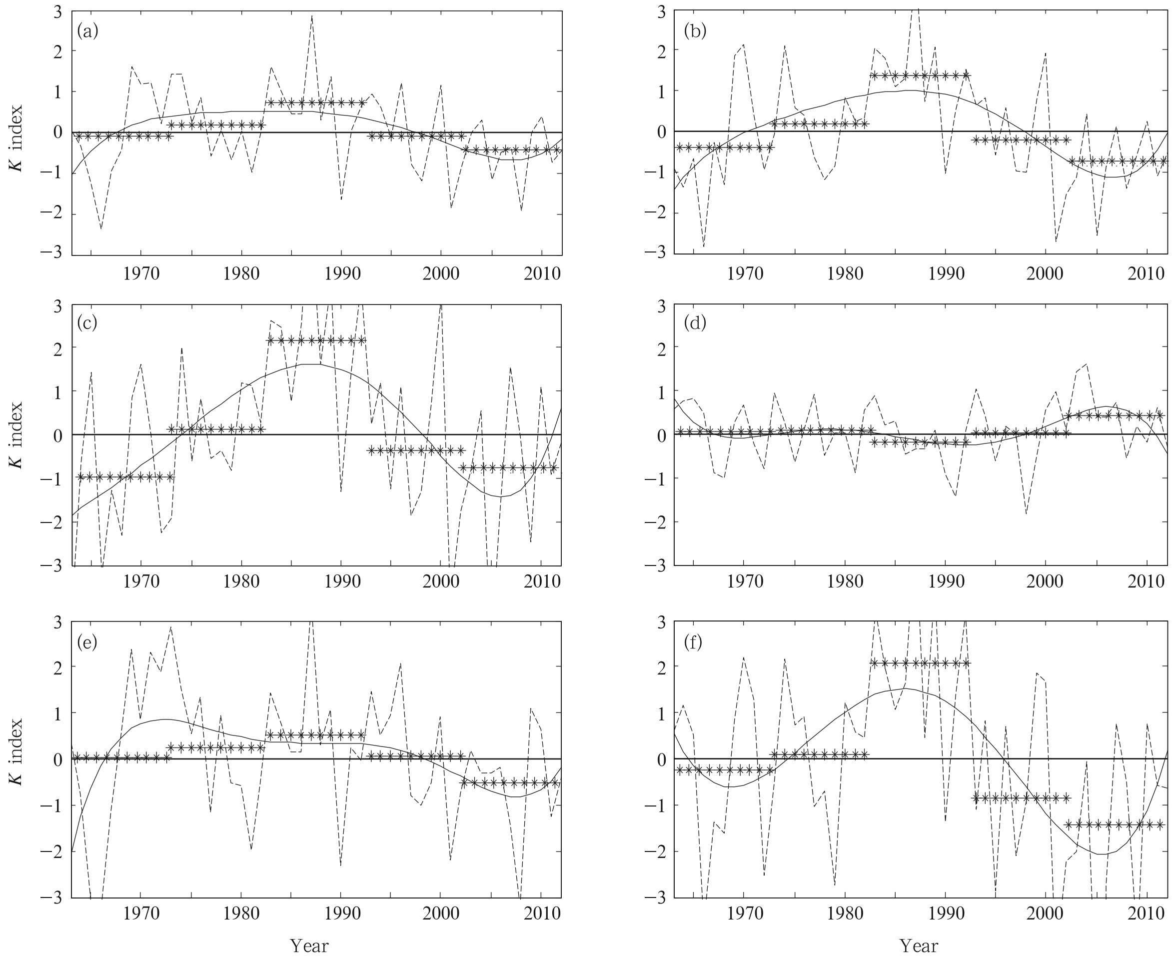

Fig. 8. The *K* index time series (dashed line) and its fifth-order polynomial (solid line) and average for each decade (asterisk) for (a) Northwest China, (b) Gansu Province, (c) Ningxia Region, (d) Qinghai Province, (e) Xinjiang Region, and (f) Shaanxi Province from 1963 to 2012.

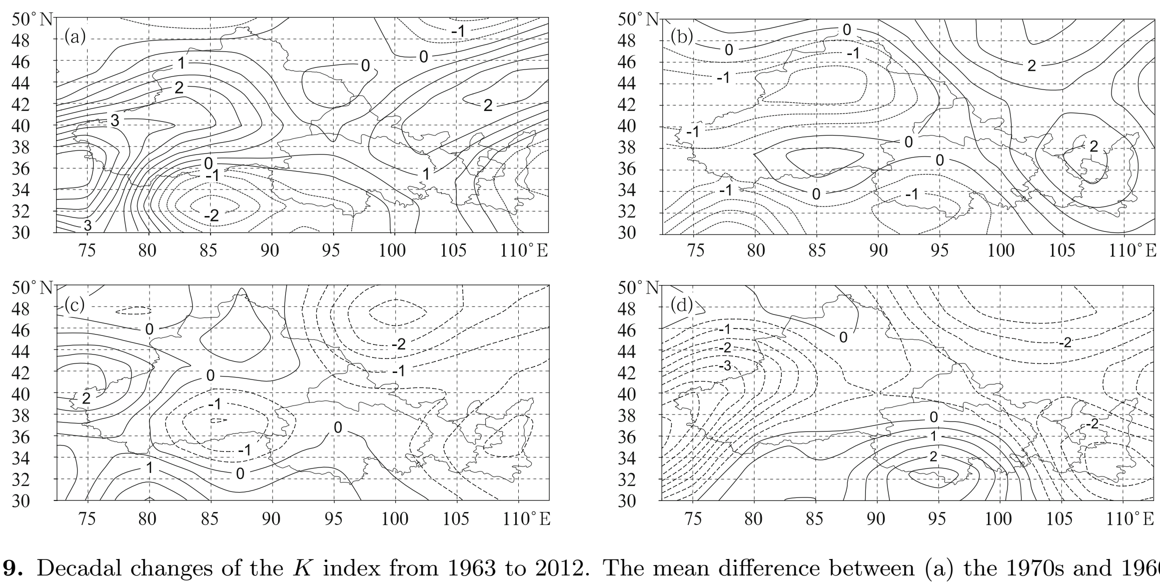

Fig. 9. Decadal changes of the *K* index from 1963 to 2012. The mean difference between (a) the 1970s and 1960s, (b) the 1980s and 1970s, (c) the 1990s and 1980s, and (d) the 2000s and 1990s.

affected by the K index. The frequency changes in southern Qinghai differed from the changes of the K index.

Comparison between the 1990s and 1980s (Fig. 9c) showed negative values in the Shaanxi-Gansu-Ningxia area, southern Xinjiang, and northern Qinghai. The minimum value was located in southern Xinjiang. Positive values were found in western and northern Xinjiang and southern Qinghai. The corresponding average extreme precipitation frequency difference (Fig. 6c) indicates that the rainfall days in southern Gansu, Ningxia, and Shaanxi were noticeably reduced, whereas those in other regions were increased or unchanged. Therefore, good correspondence was observed between the changes in the K index and the changes in extreme precipitation frequency.

Comparison between the 2000s and 1990s (Fig. 9d) showed negative values in most areas, except in central and southern Qinghai. The minimum value occurred in western Xinjiang and southern Shaanxi, whereas the maximum value occurred in southern Qinghai. With regard to the corresponding mean difference of extreme precipitation frequency between each decade (Fig. 6d), the frequency increased in most areas of Qinghai and southern Gansu, but it decreased in northern and central Gansu and northern Xinjiang, corresponding well to the K index. This analysis indicates that the change in the K index was similar to that in the extreme precipitation frequency, and the similarity was high in Qinghai, Shaanxi, Ningxia, and Gansu.

The horizontal distributions of temperature and humidity in the upper and lower troposphere for the past 10 years (2003–2012) were analyzed to explain the change in the K index (Fig. 10). Warming and moistening in the lower troposphere and cooling and drying in the upper troposphere were observed, except in southern Xinjiang. The temperature and humidity in the upper and lower troposphere significantly changed in northern Qinghai and southern Gansu. This phenomenon is consistent with the positive difference of the K index in northern Qinghai and southern Gansu. This phenomenon also exhibited a good relationship with the increased frequency of extreme precipitation in northern Qinghai and southern Gansu. The increase in temperature and humidity at low altitudes

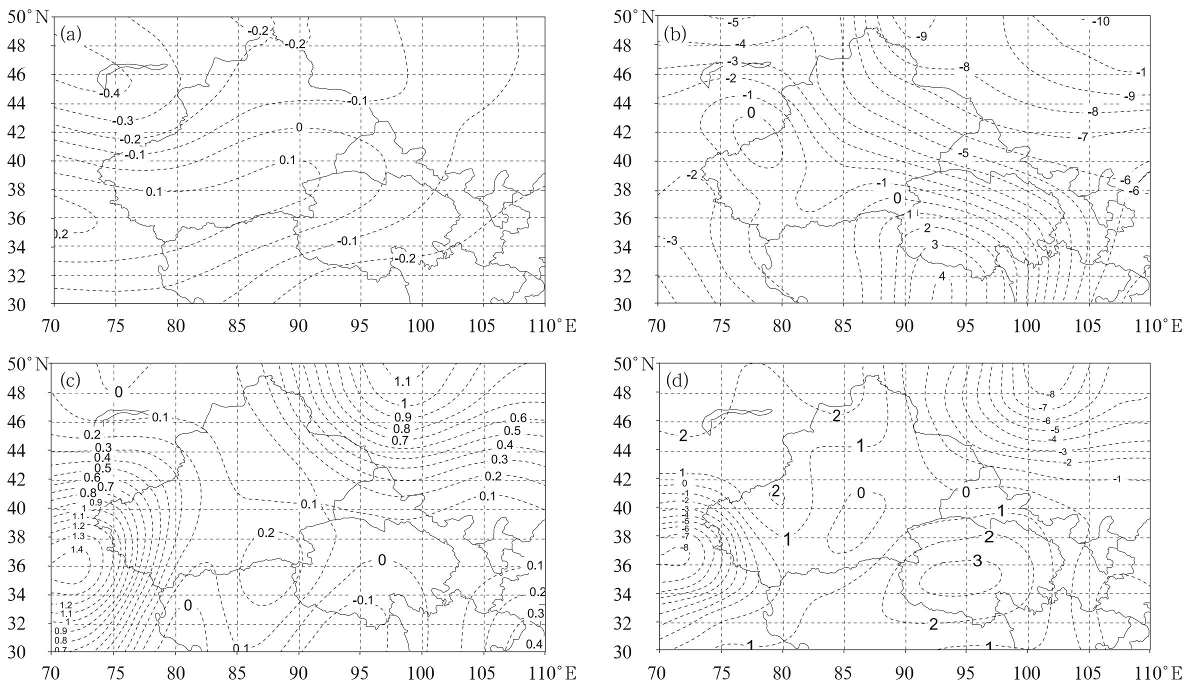

Fig. 10. (a, c) Temperature (℃) and (b, d) humidity (%) anomaly distributions in the (a, b) upper and (c, d) lower troposphere (2003 to 2012, with 1963 to 2012 as the standard).

and the decrease at high altitudes are caused by climate change in Northwest China. These changes led to the increase in the K index and thus the frequency of extreme precipitation events.

5.2 Precipitable water

The inconsistency between Figs. 9 and 6 reveals that the K index cannot fully explain the changes in extreme precipitation days. Therefore, the analysis in Section 5.1 may not be sufficient, and the influences of moisture and dynamic factors may need to be considered. The precipitable water can be expressed as

$$W = -\frac{1}{g}\int_{p_0}^{0} q\mathrm{d}p, \tag{2}$$

where q is the specific humidity (water vapor mixing ratio) of each layer, and p_0 is the surface pressure (Zhang et al., 2012).

Figure 11 shows the decadal variability of precipitable water in Northwest China. Comparison of the precipitation between the 1970s and 1960s shows that northern and western Xinjiang exhibited a moistening trend, whereas southern Xinjiang, Qinghai, southern Gansu, and Ningxia demonstrated a drying trend. This result indicates that the reduction in extreme precipitation frequency was associated with the drying trend in southern Qinghai and southern Shaanxi. Comparison of the precipitable water between the 1980s and 1970s indicates that most areas in Qinghai and Shaanxi-Gansu-Ningxia were wet, whereas Xinjiang was dry, which was consistent with the increased precipitation frequency in Qinghai and the Shaanxi-Gansu-Ningxia area. This finding also explains the decrease in the K index and the extreme precipitation frequency increase in southern Qinghai. Comparison of the precipitable water between the 1990s and 1980s indicates that western and central Xinjiang was becoming wet, whereas eastern Xinjiang was becoming dry. These observations can explain the corresponding changes in extreme precipitation frequency. Finally, Qinghai became wet and central Xinjiang became dry from the 1990s to the 2000s, and these changes accounted for the increase in extreme precipitation frequency over Qinghai and the decrease over the central Xinjiang.

5.3 Dynamical effects

In this subsection, the effects of atmospheric dynamics on precipitation in Northwest China were analyzed. The distribution of the divergence difference between 300 and 700 hPa averaged during June–August of 2003–2012 was shown in Fig. 12a. High- and low-level convergence was enhanced over the past 10 years, resulting in an increase in the divergence difference between high and low levels.

In the previous sections, the extreme precipita-

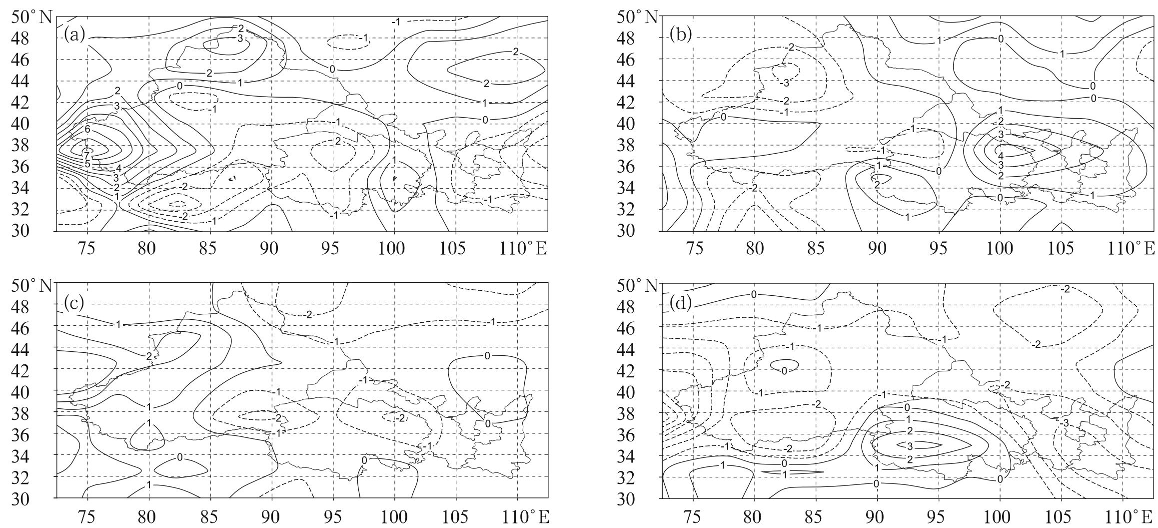

Fig. 11. Decadal changes of precipitable water (mm) from 1963 to 2012. The mean difference between (a) the 1970s and 1960s, (b) the 1980s and 1970s, (c) the 1990s and 1980s, and (d) the 2000s and 1990s.

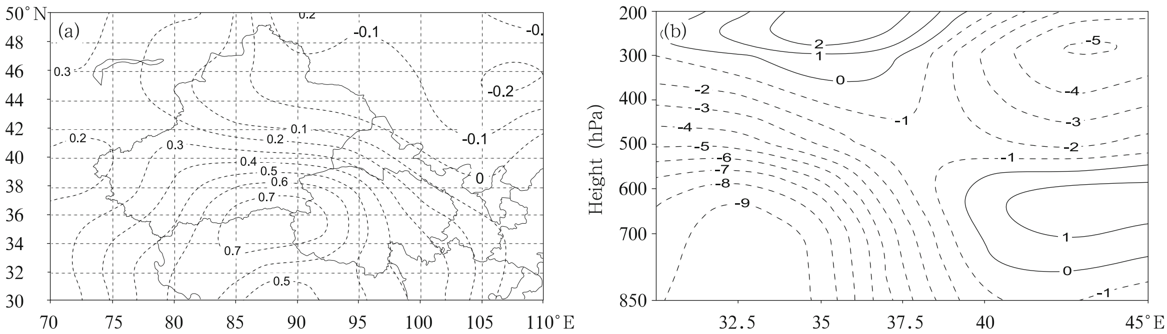

Fig. 12. (a) Distribution of the difference in divergence (10^{-12} s^{-1}) between 300 and 700 hPa averaged and (b) profiles of the vertical velocity (10^{-3} Pa s^{-1}) along 105°E averaged during July–August of 2003–2012.

tion frequency noticeably increased in southern Gansu from 2003 to 2012. To further explain the phenomenon from the dynamical perspective, the profiles of vertical velocity were plotted along 105°E over southern Gansu with the data of June–August 2003–2012 (Fig. 12b). Over 30°–40°N, negative anomalies occurred below 350 hPa, whereas positive anomalies occurred above 350 hPa. At 32.5°N, negative anomalies reached their maximum of more than –9×10^{-3} Pa s^{-1}. Strong upward motion in southern Gansu was observed, and this was conducive to extreme precipitation. Therefore, the convergence in the lower troposphere and the divergence in the upper troposphere were enhanced over the past 10 years and thus led to the strong upward motion anomalies with increased atmospheric instability and enhanced convection and precipitation.

6. Summary

The spatiotemporal distribution of the extreme precipitation frequency in Northwest China and the associated influencing factors are investigated in this study. The major results are as follows.

The highest summer extreme precipitation frequency and largest interannual difference of extreme precipitation frequency occurred in the southern parts of Qinghai, Gansu, and Shaanxi provinces in Northwest China. These areas are prone to abrupt changes of extreme precipitation frequency.

Over the past 50 years, the frequency of extreme summer precipitation events exhibited an increasing trend in Northwest China, accompanied with multi-timescale cyclical swings in the extreme precipitation frequency in local areas. The extreme precipitation frequency in the entire Northwest China and in each province/region exhibited a mutation during the late 1970s and 1990s. In particular, the extreme precipitation frequency during the late 1970s demonstrated a significant increasing trend. Qinghai showed an increasing trend, whereas Gansu and Ningxia presented a relatively flat trend. The low rainfall days in Xinjiang barely changed, and Shaanxi demonstrated a quasi-10-yr oscillation.

Northwest China can be divided into three subregions (northern, central, and southern) based on cluster analysis of the extreme precipitation frequency time series. The northern area mainly exhibited a mutation from low to high from the late 1980s to the early 1990s. Meanwhile, a low-to-high mutation occurred in the central region in the beginning of the 1990s. The southern region demonstrated a 10-yr oscillation.

Over the past 50 years, summer stratification stability, water vapor content, and atmospheric dynamical effects have influenced the extreme precipitation frequency in Northwest China. The increase in local extreme precipitation frequency was associated with enhanced summer instability, increased atmospheric moisture, and atmospheric upward motion, and vice versa.

Stratification stability and precipitable water significantly affected extreme precipitation frequency during summer in western Qinghai and the Shaanxi-Gansu-Ningxia border region. The effect of water vapor content on summer extreme precipitation frequency was significant in eastern and southern Qinghai. The increased water vapor content corresponded to the increase in extreme precipitation frequency in Qinghai Province. The effect of atmospheric upward motion on summer extreme precipitation frequency was noticeable in Qinghai and southern Gansu. The increased atmospheric upward motion corresponded with the increase in extreme precipitation frequency in Qinghai and southern Gansu.

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