Identification and Variation Characteristics of Spring Compound Low-Temperature and Rainy Events in the Eastern Hexi Corridor

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Abstract

Compound low-temperature and rainy events are among the most frequent compound extreme climate events in the eastern Hexi Corridor, and they are also important climatic indicators and meteorological disasters affecting agricultural production. Their impacts on agricultural production and the ecological environment are more severe than those of single extreme climate events. Based on daily minimum temperature and precipitation observations from 5 meteorological stations in the eastern Hexi Corridor during the springs of 1960–2024, this study identified and determined compound low-temperature and rainy events using the percentile threshold method and the maximum proximity principle, and analyzed their spatiotemporal variation characteristics using inverse distance weighted interpolation and the linear trend method. The results show that: (1) In spring and from March to May, compound low-temperature and rainy events in the eastern Hexi Corridor exhibit a spatial distribution characterized by more events in the south and fewer in the north, following the order Gulang > Tianzhu > Liangzhou > Yongchang > Minqin, with high-value areas in the shallow mountainous area of Gulang and low-value areas in the desert area of Minqin. (2) In the eastern Hexi Corridor, compound low-temperature and rainy events in spring, March, and April generally show a decreasing trend by decade and by year, while in May they generally show a trend of first increasing and then decreasing by decade and by year. The maximum frequencies and occurrence years of compound low-temperature and rainy events in spring and each month differ across the whole region and individual locations, and there are individual years in which no compound low-temperature and rainy events occurred. The research results can provide an important scientific basis and practical value for agricultural production and ecological environmental protection.

Full Text

Identification and Variation Characteristics of Spring Compound Low-Temperature and Rainy Events in the Eastern Hexi Corridor

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Abstract: Compound low-temperature and rainy events are among the frequently occurring compound extreme climate events in the eastern Hexi Corridor, and they are also one of the important climatic indicators and meteorological disasters affecting agricultural production. Their harm to agricultural production and the ecological environment is more serious than that caused by a single extreme climate event. Using daily minimum temperature and precipitation observation data from five meteorological stations in the eastern Hexi Corridor during the spring seasons of 1960–2024, the percentile threshold method and the maximum proximity principle were used to identify and determine compound low-temperature and rainy events, and the inverse distance weighted interpolation method and linear trend method were used to analyze their spatiotemporal variation characteristics. The results show that: (1) In spring and in March–May, compound low-temperature and rainy events in the eastern Hexi Corridor all exhibit a distribution pattern of more events in the south and fewer in the north, specifically Gulang > Tianzhu > Liangzhou > Yongchang > Minqin. The high-value area is in the low-mountain area of Gulang, and the low-value area is in the desert area of Minqin. (2) In the eastern Hexi Corridor, compound low-temperature and rainy events in spring and in March and April generally show a decreasing trend with respect to decades and years; in May, they generally show a trend of first increasing and then decreasing with respect to decades and years. The maximum frequency and occurrence years of compound low-temperature and rainy events in spring and in each month differ for the whole region and for individual locations, and in some individual years no compound low-temperature and rainy events occurred. The research results can provide important scientific evidence and practical value for agricultural production and ecological environmental protection.

Keywords: identification; variation characteristics; compound low-temperature and rainy event; percentile threshold method; Hexi Corridor

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Against the background of global climate warming, the impact of extreme low-temperature events on the economy and society also deserves attention[1–3]. Extreme low-temperature events are often accompanied by freezing rain and snow disasters, and can easily cause serious economic losses. Extensive research has been carried out in academia on extreme low-temperature events, and it has been found that their variation characteristics are more pronounced than those of high-temperature events[4–5]. Studies have found that extreme low-temperature events across China exhibit significant temporal and spatial differences. Yang Jinhu et al.[6] pointed out that, during 1960–2004, the decrease in extreme low-temperature events in Northwest China was far greater than the increase in extreme high-temperature events, reflecting that the response of extreme low-temperature events in this region is more sensitive during the process of climate warming. Liu Yaxing et al.[7] showed that, during 1961–2006, winter extreme temperatures in China generally exhibited an upward trend; among them, changes in the frequency of winter low-temperature events in East China were the most prominent, while changes in the number of severe-cold days were relatively significant in northern China. From the perspective of the country as a whole, Fu Dongxue et al.[8] analyzed the spatiotemporal variation of extreme low temperatures during the winter half-years of 1955–2006, and found that the frequency of extreme low temperatures nationwide generally declined, with an obvious abrupt change occurring around 1983, and that differences among regions were significant. Chen Haishan et al.[9] considered that winter extreme low-temperature events during 1959–2008 were closely related to synoptic-scale transient wave activity. Han Yongqiu et al.[10] further pointed out that extreme low-temperature events in the winter half-year during 1961–2012 showed a decreasing trend, with an obvious abrupt change in 1986; this change may be closely related to the weakening of the Siberian High and its southward shift.

According to the research in the IPCC Sixth Assessment Report[11], the frequency of extreme precipitation events on a global scale shows an increasing trend. This phenomenon is most prominent in mid- and high-latitude regions, and has increased significantly since the 1950s. This change has been verified in many countries and regions[12–15], and extreme precipitation events have generally increased over the past 50 a. As far as China is concerned, although precipitation intensity in most regions shows an increasing trend[16–19], North China exhibits a unique weakening tendency,

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The frequency of heavy-precipitation events has also declined[20–22]. Observational data indicate that changes in China' s precipitation pattern are consistent with the overall global trend, while also showing regional differences. In the core conclusions document of the IPCC Sixth Assessment Report—the Summary for Policymakers—the concept of "compound events" was systematically discussed for the first time[11]. The report defines them as combined events formed by two or more extreme weather or climate events that occur simultaneously at the same or different locations, or occur successively in time; their disaster-causing impacts usually far exceed those of a single extreme event[23–24]. With global warming, a single meteorological indicator can no longer fully reflect the complex characteristics of extreme climate, making compound extreme events a focus of academic attention. Existing studies have mostly concentrated on compound hot-dry events, and have confirmed that, under climate warming, the frequency of compound hot-dry events has increased significantly[25-27]. Notably, in recent years, extreme low-temperature and extreme-precipitation events have also increased simultaneously worldwide. When the two occur together to form compound cold-and-rainy events, their synergistic effects can impose more severe impacts on agricultural production and the socioeconomic system than a single event. For example, in February 2022, southern China experienced the strongest compound low-temperature and freezing-rain disaster in 60 a, with direct economic losses reaching 7.89×10^{10} yuan[28]. However, at present there are very few descriptions of the research background and domestic and international frontiers and progress regarding compound cold-and-rainy events, and research on this type of compound event is also very limited[29]. It is therefore urgent to strengthen research and analysis on the evolution patterns after the compounding of extreme low temperature and extreme precipitation.

The eastern Hexi Corridor lies in the ecotone between the Loess Plateau and the Gobi Desert. This region is highly sensitive in its response to climate change, has a fragile ecological environment, and is vulnerable to multiple meteorological disasters such as drought, sandstorms, rainstorms, extreme high temperatures, and low-temperature freezing injury. Spring is the season in which cold and warm air masses alternate frequently in this region, and it also coincides with the critical period for crop sowing, seedling emergence, and growth. Low-temperature and rainy weather during this period not only seriously disrupts spring plowing and spring sowing and the normal development of crops, but also has considerable impacts on local crop farming and animal husbandry. However, no studies have yet been reported on spring compound cold-and-rainy events in this region. Therefore, based on daily observations of extreme minimum temperature and precipitation from five meteorological stations in the eastern Hexi Corridor during 1960-2024, this study explores and identifies spring compound cold-and-rainy events, and conducts an in-depth analysis of their spatiotemporal evolution patterns and potential impacts on agricultural production. The results will help improve forecasting and early-warning capabilities for compound cold-and-rainy events, and provide theoretical support for mitigating agroecological hazards and formulating scientific defensive measures.

1 Data and Methods

1.1 Overview of the Study Area

The study area is located in the eastern Hexi Corridor in central Gansu Province. Its distinctive feature is that it lies in the transitional convergence zone of three major geomorphic units—the Qinghai-Tibet Plateau, the Loess Plateau, and the Mongolian Plateau—at 36°29′-39°27′N and 101°41′-104°16′E. The terrain slopes from southwest to northeast, with elevation gradually decreasing from 2500-4850 m on the slopes of the Qilian Mountains in the southwest to 1300-2000 m in the northeast. According to geomorphic characteristics, it can be divided into four typical regions: the alpine mountain area of the Tianzhu Qilian Mountains in the south, the shallow mountain area of Yongchang in the north and Gulang in the south, the Liangzhou oasis plain in the central part, and the Minqin desert area in the north (Fig. 1). The eastern Hexi Corridor has pronounced continental temperate arid–semi-arid climate characteristics. Meteorological data (30-a mean for 1991-2020) show a large north–south temperature difference (0.7-9.4 °C), scarce precipitation (120.8–431.1 mm), abundant sunshine (2649.5–3184.4 h), and strong evaporation (1567.9-2631.3 mm), with evaporation reaching 3.6–21.8 times the precipitation. In spring, the climatic characteristics are temperatures of 0.7-11.2 °C and precipitation of 21.9–85.0 mm. As a typical climatic transition zone, the eastern Hexi Corridor exhibits high sensitivity to climate change[30].

In-figure labels: elevation/m; 4853; 1247; meteorological station; study-area boundary; county boundary; Yongchang; Minqin; Liangzhou; Gulang; Tianzhu; 0; 50 km.

Note: Prepared based on the standard map with approval No. GS(2024)0650 from the Standard Map Service website of the Ministry of Natural Resources; the base-map boundaries were not modified. The same below.

Fig. 1 Spatial distribution of terrain and meteorological stations in the eastern Hexi Corridor

1.2 Data Sources

The data used in this study come from five national basic meteorological stations in the eastern Hexi Corridor, namely Yongchang, Minqin, Liangzhou, Gulang, and Tianzhu (Wushaoling Station). The data elements are daily minimum temperature (hereafter referred to as low temperature) and daily precipitation, covering the spring season (March–May) during 1960–2024. The Meteorological Information Center of the Gansu Provincial Meteorological Bureau provided all data

The data are characterized by complete sequences and good continuity, have undergone strict quality control, and are highly reliable.

1.3 Research methods

The inverse-distance-weighted interpolation method in ArcGIS[31] was used to generate spatial distribution maps of compound low-temperature and rainy events. Based on the linear trend method, the long-term variation trend in the annual frequency of compound low-temperature and rainy events was analyzed. The linear regression model is:

$$x_i = b + a \times t_i \tag{1}$$

where x_i is the frequency of compound low-temperature and rainy events in year i; b is the constant term; a is the climatic tendency rate; and t_i is the year corresponding to year i[32]. The significance of the trend was tested using the climatic trend coefficient, i.e., the correlation coefficient between the variable and the time series. According to Monte Carlo simulation results[33], at significance levels of $\alpha = 0.1$, 0.05, and 0.01, the corresponding critical values of the trend coefficient are 0.306, 0.365, and 0.443, respectively. When the absolute value of the trend coefficient exceeds the above critical values, the change trend is indicated as relatively significant, significant, and highly significant, respectively.

2 Results and analysis

2.1 Identification and determination of compound low-temperature and rainy events

The definition of compound extreme events follows the "maximum proximity principle,"that is, if two types of extreme events at the same site occur within the same 1 d (spatiotemporal compounding) or occur consecutively (temporal compounding), they are defined as compound extreme events[34]. Single extreme events were determined based on the percentile threshold method[35]. The specific procedure was as follows: for a given location, the daily low-temperature (precipitation) series from March to May during 1960-2024 was ranked in ascending order year by year and month by month, and the 10th (90th) percentile was selected as the threshold for low-temperature (precipitation) events. Thus, the low-temperature (precipitation) thresholds for March–May in each year were obtained. The mean value of the multi-year low-temperature (precipitation) threshold for a given location and month was defined as the total threshold of low temperature (precipitation) for that location and month. The total thresholds of low temperature and precipitation for each location and month in the eastern Hexi Corridor are shown in Table 1. When the daily low temperature at a location is $\leq$ the total threshold, and the precipitation amount on the previous 1 d, the same day, or the following 1 d is $\geq$ the total threshold, it is recorded as one compound low-temperature and rainy event; alternatively, when the daily precipitation at a location is $\geq$ the total threshold, and the low temperature on the previous 1 d, the same day, or the following 1 d is $\leq$ the total threshold, it is also recorded as one compound low-temperature and rainy event. If compound low-temperature and rainy events occur continuously for 2 d or more, they are counted as one compound low-temperature and rainy event. For each location, spring compound low-temperature and rainy events are the sum for March–May, and the regional compound low-temperature and rainy events are the mean of the five stations.

Table 1 Total threshold values of low temperature and precipitation in various regions of the eastern Hexi Corridor from March to May during 1960–2024

Place name	Low-temperature total threshold / °C	Low-temperature total threshold / °C	Low-temperature total threshold / °C	Precipitation total threshold / mm	Precipitation total threshold / mm	Precipitation total threshold / mm
	March	April	May	March	April	May
Yongchang	−11.6	−4.9	0.6	0.7	1.4	2.9
Minqin	−9.9	−2.8	4.3	0.2	0.4	1.3
Liangzhou	−7.6	−1.7	4.2	0.6	1.0	2.3
Gulang	−9.9	−3.4	1.9	2.1	3.8	6.2
Tianzhu	−15.2	−9.7	−4.0	1.3	2.5	5.3

2.2 Spatiotemporal variation characteristics of compound low-temperature and rainy events

2.2.1 Spatial distribution The eastern Hexi Corridor is located on the eastern flank of the Qilian Mountains. Its terrain is diverse, including mountains and hills as well as plains and deserts, and the spatial distribution of compound low-temperature and rainy events varies by region. During spring and March–May from 1960 to 2024, compound low-temperature and rainy events in the eastern Hexi Corridor as a whole showed a spatial distribution characterized by more events in the south and fewer in the north (Fig. 2). The frequency of compound low-temperature and rainy events was 1.6–3.9 times in spring, 0.4–1.4 times in March, 0.5–1.2 times in April, and 0.6–1.6 times in May. In spring and during March–May, the spatial distribution trend of compound low-temperature and rainy events was generally Gulang > Tianzhu > Liangzhou > Yongchang > Minqin; that is, Gulang in the southern shallow-mountain area was the high-value area for compound low-temperature and rainy events, while Minqin in the desert area was the low-value area.

This may be because the southern mountainous area is at a high elevation and is located on the windward slope and slope crest on the northeastern side of the Qilian Mountains. As weather systems move from northwest to southeast, the effects of topographic blocking and uplift cause cold air to accumulate there, making convective precipitation more likely and precipitation amounts larger. As a result, compound low-temperature and rainy events in the southern mountainous area occur more frequently than in the northern shallow-mountain area, the oasis plain, and the desert area. In addition, although the high, cold mountainous area along the slope in Tianzhu has the highest elevation, it is located near the slope crest, where uplift is not very pronounced and may even be replaced by subsidence. This is not conducive to the accumulation of cold air or the occurrence of convective precipitation, so compound low-temperature and rainy events in Tianzhu are fewer than in Gulang. Therefore, Gulang in the shallow-mountain area is a high-value area for compound low-temperature and rainy events. By contrast, Minqin in the northern desert area is mainly controlled by the westerly circulation system. The atmospheric water-vapor content is relatively low, the desert-climate characteristics are obvious, and precipitation is scarce. Even when marked extreme low temperatures occur, the probability of forming compound low-temperature and rainy events remains low; thus, Minqin in the desert area is a low-value area for compound low-temperature and rainy events. It can therefore be seen that the spatial distribution of compound low-temperature and rainy events in the eastern Hexi Corridor is the result of the combined influence of elevation, topography and landforms, and atmospheric circulation systems.

2.2.2 Temporal variation

(1) Interdecadal variation

The frequency of compound low-temperature and rainy events in the eastern Hexi Corridor showed an overall decreasing trend by decade in spring and in March–April (Table 2), although individual decades also exhibited relatively low or relatively high values. Since the 21st century, compound low-temperature and rainy events have decreased markedly. From 1960–1969 to 2020–2024, spring compound low-temperature and rainy events in the whole region and in Yong···

Figure 2 panels and legends

- **(a) Spring**
  - Stations: Minqin, Yongchang, Liangzhou, Gulang, Tianzhu
  - Legend: meteorological station; study-area boundary; county boundary
  - Frequency/times: 2.0, 2.4, 2.8, 3.2, 3.4, 3.6
  - Scale: 0–50 km
- **(b) March**
  - Stations: Minqin, Yongchang, Liangzhou, Gulang, Tianzhu
  - Legend: meteorological station; study-area boundary; county boundary
  - Frequency/times: 0.6, 0.8, 1.0, 1.2, 1.4, 1.6
  - Scale: 0–50 km
- **(c) April**
  - Stations: Minqin, Yongchang, Liangzhou, Gulang, Tianzhu
  - Legend: meteorological station; study-area boundary; county boundary
  - Frequency/times: 0.6, 0.7, 0.8, 0.9, 1.0, 1.1
  - Scale: 0–50 km
- **(d) May**
  - Stations: Minqin, Yongchang, Liangzhou, Gulang, Tianzhu
  - Legend: meteorological station; study-area boundary; county boundary
  - Frequency/times: 0.8, 0.9, 1.0, 1.1, 1.2, 1.3
  - Scale: 0–50 km

Fig. 2 Spatial distributions of the average frequency of compound low-temperature and rainy events in the eastern Hexi Corridor in spring and in each month during 1960–2024

Chang, Minqin, Liangzhou, Gulang, and Tianzhu decreased in spring by 1.5, 1.0, 1.7, 1.3, 2.9, and 0.8 times, respectively; in March by 1.0, 1.1, 0.9, 0.7, 1.9, and 0.4 times, respectively; and in April by 0.6, −0.2, −0.4, 0.7, 1.0, and 1.0 times, respectively. In May, the compound low-temperature and rainy events generally showed a trend of first increasing and then decreasing with the decades. They reached the maximum in 1980–1989 and the minimum in 2020–2024, with 1960–1969 being the second lowest. From 1960–1969 to 1980–1989, they increased by 0.9, 0.4, 0.7, 1.4, 1.2, and 0.7 times, respectively; from 1980–1989 to 2020–2024, they decreased by 0.8, 0.5, 1.1, 1.3, 1.2, and 0.1 times, respectively.

(2) Interannual variation

Figure 3 shows the interannual variation trends in the frequency of compound low-temperature and rainy events in spring and from March to May in the eastern Hexi Corridor during 1960–2024. The climatic tendency rates and trend coefficients are shown in Table 3. For the whole region and all localities, the annual frequency of compound low-temperature and rainy events in spring and in March–April showed a decreasing trend. In May, the trends in annual frequency were not very consistent: Yongchang and Minqin showed decreasing trends, whereas the whole region and the other localities showed increasing trends. In terms of the absolute value of the climatic tendency rate, the order in spring was Gulang > whole region > Minqin > Liangzhou > Yongchang > Tianzhu; in March it was Gulang > whole region > Yongchang > Liangzhou > Minqin > Tianzhu; in April it was Tianzhu > Gulang > Liangzhou > whole region > Minqin > Yongchang; and in May it was Tianzhu > Minqin = Gulang > whole region > Liangzhou > Yongchang. Only a few individual regions and individual months passed the significance test for the climatic trend coefficient (Table 3). Overall, the decreasing or increasing trends of compound low-temperature and rainy events were not obvious.

Table 4 gives the maximum annual frequencies and occurrence years of compound low-temperature and rainy events in spring and in each month for the whole region, Yongchang, Minqin, Liangzhou, Gulang, and Tianzhu in the eastern Hexi Corridor. The interannual fluctuations of compound low-temperature and rainy events in the whole region and in each locality were relatively large. The maximum annual frequency in spring was 6 times for the whole region, and each

Table 2 Decadal anomalies in the frequency of compound low-temperature and rainy events in spring and in each month in the eastern Hexi Corridor during 1960–2024

Tab. 2 Decadal distances of compound low temperature and rainfall events frequency in the eastern Hexi Corridor in spring and every month during 1960

—2024
Unit: times

Period	Location	1960–1969	1970–1979	1980–1989	1990–1999	2000–2009	2010–2019	2020–2024
Spring	Whole region	0.0	0.6	0.7	0.1	−0.3	−0.1	−1.5
Spring	Yongchang	−0.1	0.4	0.8	0.2	−0.5	0.0	−1.1
Spring	Minqin	0.3	0.6	0.4	−0.6	−0.2	0.1	−1.4
Spring	Liangzhou	−0.4	0.7	1.2	0.2	−0.4	−0.2	−1.7
Spring	Gulang	0.2	0.8	1.0	0.4	−0.9	−0.3	−2.7
Spring	Tianzhu	0.0	0.3	−0.2	0.4	0.2	−0.3	−0.8
March	Whole region	0.4	0.0	0.5	−0.2	−0.1	−0.2	−0.6
March	Yongchang	0.4	−0.5	0.8	0.0	−0.3	−0.3	−0.7
March	Minqin	0.5	0.0	−0.1	−0.3	0.0	0.2	−0.4
March	Liangzhou	0.2	−0.1	0.9	−0.3	−0.2	−0.1	−0.5
March	Gulang	0.7	0.6	0.4	−0.3	−0.3	−0.7	−1.2
March	Tianzhu	0.0	−0.2	0.3	0.0	0.3	−0.2	−0.4
April	Whole region	0.2	0.4	−0.2	0.1	−0.2	−0.1	−0.4
April	Yongchang	−0.2	0.5	−0.1	0.0	−0.2	0.1	0.0
April	Minqin	0.1	0.6	0.1	−0.2	−0.2	−0.1	−0.3
April	Liangzhou	0.1	0.5	−0.4	0.4	−0.4	−0.2	−0.6
April	Gulang	0.2	0.3	0.1	0.1	−0.2	−0.1	−0.8
April	Tianzhu	0.7	0.1	−0.5	0.3	−0.2	−0.4	−0.3
May	Whole region	−0.6	0.2	0.3	0.2	0.0	0.2	−0.5
May	Yongchang	−0.4	0.3	0.0	0.1	−0.1	0.1	−0.5
May	Minqin	−0.2	0.1	0.5	0.0	0.1	0.1	−0.6
May	Liangzhou	−0.8	0.2	0.6	0.0	0.1	0.0	−0.7
May	Gulang	−0.7	−0.1	0.5	0.6	−0.4	0.5	−0.7
May	Tianzhu	−0.7	0.4	0.0	0.1	0.1	0.3	−0.1

At individual locations, the frequency was 5-9 times; in March, April, and May, the whole-region frequency was 3 times in each case, and the frequencies at individual locations were 3-6, 3-5, and 3-5 times, respectively. For the whole region and for each location, the years with the highest annual frequency in spring and in each month were quite inconsistent, and all occurred before 2010, indicating that compound low-temperature and rainy events decreased markedly after 2010. For the whole region and for each location, in spring and in each month, there were individual years in which no compound low-temperature and rainy events occurred.

3 Discussion

This study focuses on the identification and determination of compound low-temperature and rainy events in the eastern Hexi Corridor and on analysis of their spatiotemporal variation characteristics. Although certain research results have been obtained, several issues still require further discussion. First, this study has not yet addressed the anomalous circulation characteristics or the occurrence and development mechanisms of compound low-temperature and rainy events. In view of the complexity of the causes of compound extreme events noted in the IPCC Sixth Assessment Report—their driving factors may not have obvious associations—subsequent research should focus on exploring how climate warming affects the anomalous occurrence mechanisms of such compound events, thereby significantly improving forecasting and early-warning capability and the effectiveness of risk response, and laying a foundation for formulating scientific disaster-prevention and mitigation strategies. Second, this paper used only daily minimum temperature and precipitation data from five national meteorological stations; problems such as sparse station coverage, uneven spatial representativeness, and limited coverage remain. Moreover, the intensity and persistence of compound low-temperature and rainy events were not analyzed, which constrains the accuracy and refinement of the research conclusions. In the future, data from more regional observation stations should be integrated to build a higher-resolution research framework, accurately and finely characterize the spatiotemporal heterogeneity of compound low-temperature and rainy events, and better reveal the true changes in compound low-temperature and rainy events in the eastern Hexi Corridor.

In addition, agriculture is one of the sectors most sensitive to climate change and extreme climate events. The eastern Hexi Corridor is a sensitive area to climate change and a region where extreme climate events occur frequently; it is also a vulnerable area for agricultural production. Climate change has produced a series of impacts on crop growth and development, yield and quality, planting structure, geographic distribution, and physiological ecology in the eastern Hexi Corridor, and the impacts of extreme compound climate events

Figure 3. Interannual variation in the frequency of compound low-temperature and rainy events in the eastern Hexi Corridor during spring and in each month from 1960 to 2024.

Subpanels: (a) Spring; (b) March; (c) April; (d) May.
Axes: frequency; year.
Legend: entire region; Liangzhou; Yongchang; Gulang; Minqin; Tianzhu.

The effect is more pronounced[36–37]. Compound low-temperature and rainy events are one of the important climatic indicators and meteorological disasters affecting agricultural production in spring in the eastern Hexi Corridor. On the one hand, spring compound low-temperature and rainy events in the eastern Hexi Corridor lower soil temperature, delaying crop emergence and development, and even hindering seedling growth; they seriously affect crop growth, leading to yield reduction or even total crop failure. On the other hand, compound low-temperature and rainy events increase soil and air humidity, causing soil compaction, reducing the emergence rate, and promoting the breeding and spread of pests and diseases, thereby increasing agricultural disaster losses. Meanwhile, compound low-temperature and rainy events create a microclimatic environment characterized by low temperature and insufficient sunshine, seriously affecting crop yield, quality, and the stability of agricultural production, and in turn affecting food security and economic income[38–39]. Therefore, future work urgently needs to investigate the mechanisms by which compound low-temperature and rainy events affect agricultural production, propose effective defensive countermeasures suitable for low-temperature and rainy events, and actively respond to their impacts on agricultural production.

Table 3. Climate tendency rate and trend coefficient of the annual frequency of compound low-temperature and rainy events in the eastern Hexi Corridor in spring and each month during 1960–2024

Period	Item	Entire region	Yongchang	Minqin	Liangzhou	Gulang	Tianzhu
Spring	Tendency rate / times·$(10a)^{-1}$	−0.205	−0.133	−0.195	−0.194	−0.393	−0.109
Spring	Trend coefficient	−0.293	−0.151	−0.261	−0.214	−0.332*	−0.116
March	Tendency rate / times·$(10a)^{-1}$	−0.121	−0.119	−0.057	−0.097	−0.299	−0.032
March	Trend coefficient	−0.307*	−0.202	−0.149	−0.188	−0.433***	−0.069
April	Tendency rate / times·$(10a)^{-1}$	−0.101	−0.007	−0.100	−0.114	−0.132	−0.151
April	Trend coefficient	−0.291	−0.014	−0.267	−0.266	−0.242	−0.257

Period	Item	Entire region	Yongchang	Minqin	Liangzhou	Gulang	Tianzhu
May	Tendency rate / times·$(10a)^{-1}$	0.017	−0.007	−0.038	0.010	0.038	0.074
May	Trend coefficient	0.045	−0.017	−0.083	0.034	0.058	0.137

Note: , ** indicate that the trend coefficient passed the significance test at the levels of $\alpha = 0.1$ and $\alpha = 0.01$, respectively.

Table 4. Maximum annual frequency and occurrence year of compound low-temperature and rainy events in the eastern Hexi Corridor in spring and each month during 1960–2024

Place name	Spring frequency / times	Spring year	March frequency / times	March year	April frequency / times	April year	May frequency / times	May year
Entire region	6	1979, 2010	3	1962, 1979	3	1975	3	1992
Yongchang	8	1989	5	1982	3	1975, 1989, 2010	3	1977, 1992, 2016
Minqin	5	1975, 1979, 1982, 2010	3	1969, 1979	3	1975	4	1961
Liangzhou	8	1979	3	1962, 1969, 1979, 1985, 1989, 2010	3	1963, 1979	4	1980
Gulang	9	1979	6	1962	3	1963, 1979, 1990, 1996, 2003, 2010	5	1992
Tianzhu	7	1992	4	2007	5	1960	5	1992

4 Conclusion

(1) Using the percentile-threshold method, the 10th (90th) percentile value of the daily low-temperature (precipitation) series was defined as the threshold for a low-temperature (precipitation) event. When the daily low temperature (precipitation) was lower (higher) than the threshold, it was identified as a low-temperature (precipitation) event. When low-temperature and precipitation events occurred on the same day at the same station, or when low-temperature and precipitation events occurred successively at the same station, they were defined as a compound low-temperature and rainy event.

(2) Compound low-temperature and rainy events in spring and in March–May in the eastern Hexi Corridor all exhibited a spatial distribution characterized by more events in the south and fewer in the north. Gulang County in the southern mountainous area was the high-value area for compound low-temperature and rainy events, whereas Minqin County in the desert area was the low-value area.

(3) In the eastern Hexi Corridor, compound low-temperature and rainy events in spring and in March and April generally showed a decreasing trend with both decade and year, with the fewest occurring in 2020–2024. In May, they generally showed a trend of first increasing and then decreasing with decade and year, with the fewest occurring in 1960–1969. The maximum frequencies and occurrence years of compound low-temperature and rainy events in spring and in March–May differed among the entire region and the various localities, and in each case there were individual years in which no compound low-temperature and rainy events occurred.

References

[1] Su B D, Jiang T, Jin W B. Recent trends in observed temperature and precipitation extremes in the Yangtze River Basin, China[J]. Theoretical and Applied Climatology, 2006, 83(1-4): 139-151.

[2] Yang J H, Ren C Y, Jiang Z H. Characteristics of extreme temperature event and its response to regional warming in northwest China in past 45 years[J]. Chinese Geographical Science, 2008, 18(1): 70-76.

[3] Pal I, Al-Tabbaa A. Long-term changes and variability of monthly extreme temperatures in India[J]. Theoretical and Applied Climatology, 2010, 100(1-2): 45-56.

[4] Brabson B B, Palutikof J P. The evolution of extreme temperatures in the central England temperature record[J]. Geophysical Research Letters, 2002, 29(24): 2163, doi: 10.1029/2002GL015964.

[5] Alexander L V, Zhang X B, Peterson T C, et al. Global observed changes in daily climate extremes of temperature and precipitation[J]. Journal of Geo-

physical Research, 2006, 111(D5): D05109,

doi: 10.1029/2005JD006290.

[6] Yang Jinhu, Jiang Zhihong, Wei Feng, et al. Variability of extreme high temperature and low temperature in Northwest China over the past 45 years and their response to regional warming[J]. Arid Land Geography, 2006, 29(5): 625-631. [Yang Jinhu, Jiang Zhihong, Wei Feng, et al. Variability of extreme high temperature and low temperature and their response to regional warming in northwest China in recent 45 years[J]. Arid Land Geography, 2006, 29(5): 625-631.]

[7] Liu Yaxing, Fan Guangzhou, Dong Yiping, et al. Variations of winter daily mean temperature and extreme temperature in China over the past 46 years[J]. Journal of Chengdu University of Information Technology, 2010, 25(3): 286-292. [Liu Yaxing, Fan Guangzhou, Dong Yiping, et al. Variations of winter daily average temperature and extreme temperature in the recently 46 years in China[J]. Journal of Chengdu University of Information Technology, 2010, 25(3): 286-292.]

[8] Fu Dongxue, Sun Zhaobo, Li Zhongxian, et al. Spatial and temporal variation characteristics of extreme low temperature in China during the winter half-year from 1955 to 2006[J]. Journal of the Meteorological Sciences, 2011, 31(3): 274-281. [Fu Dongxue, Sun Zhaobo, Li Zhongxian, et al. Spatial and temporal features of China extreme minimum temperature in winter half year during 1955–2006[J]. Journal of the Meteorological Sciences, 2011, 31(3): 274-281.]

[9] Chen Haishan, Liu Lei, Zhu Yuejia. Possible linkage between winter extreme low-temperature events in China and synoptic-scale transient waves[J]. Science China: Earth Sciences, 2012, 42(12): 1951-1965. [Chen Haishan, Liu Lei, Zhu Yuejia. Possible linkage between winter extreme low temperature events over China and synoptic-scale transient wave activity[J]. Science China: Earth Sciences, 2012, 42(12): 1951-1965.]

[10] Han Yongqiu, Zhou Liantong, Huang Ronghui. Spatiotemporal characteristics of extreme low-temperature events in China during the winter half-year and their relationship with the East Asian winter monsoon[J]. Climatic and Environmental Research, 2021, 26(1): 1-17. [Han Yongqiu, Zhou Liantong, Huang Ronghui. Characteristics of the extreme low temperature events in China during boreal winter and its relationship to East Asian Winter Monsoon[J]. Climatic and Environmental Research, 2021, 26(1): 1-17.]

[11] IPCC. Climate change 2021: The physical science basis[M]. Cambridge: Cambridge University Press, 2021.

[12] Tank A M G K, Können G P. Trends in indices of daily temperature and precipitation extremes in Europe, 1946–1999[J]. Journal of Climate, 2003, 16(22): 3665-3680.

[13] Kunkel K E, Easterling D R, Redmond K, et al. Temporal variations of

extreme precipitation events in the United States 1895—2000[J]. Geophysical Research Letters, 2003, 30(17): 1900, doi: 10.1029/2003GL018052.

[14] Zhai P M, Zhang X B, Wan H, et al. Trends in total precipitation and frequency of daily precipitation extremes over China[J]. Journal of Climate, 2005, 18(7): 1096-1108.

[15] Re M, Barros V R. Extreme rainfalls in SE south America[J]. Climatic Change, 2009, 96(1-2): 119-136.

[16] Fu G B, Yu J J, Yu X B, et al. Temporal variation of extreme rainfall events in China, 1961—2009[J]. Journal of Hydrology, 2013, 487: 48-59.

[17] Cheng Ying, Song Xingyu, Fu Zhengxu, et al. New characteristics of changes in precipitation of different intensities and the atmospheric humidity index in the upper reaches of the Yellow River over the past 60 years[J]. Arid Land Geography, 2024, 47(8): 1327-1337. [Cheng Ying, Song Xingyu, Fu Zhengxu, et al. New characteristics of various intensity precipitation and atmospheric humidity index in the upper reaches of the Yellow River in recent 60 years[J]. Arid Land Geography, 2024, 47(8): 1327-1337.]

[18] Zhang Xinhan, Zhao Wenting, Jiao Juying, et al. Spatiotemporal evolution characteristics of extreme precipitation events on the Loess Plateau from 1960 to 2023[J]. Arid Land Geography, 2025, 48(7): 1153-1166. [Zhang Xinhan, Zhao Wenting, Jiao Juying, et al. Spatiotemporal evolution characteristics of extreme precipitation events on the Loess Plateau from 1960 to 2023[J]. Arid Land Geography, 2025, 48(7): 1153-1166.]

[19] Liu Jinghui, Yuan Xushan, Li Yanmin, et al. Spatiotemporal characteristics of extreme precipitation in the Ili River Basin based on CMIP6[J]. Arid Land Geography, 2025, 48(8): 1329-1341. [Liu Jinghui, Yuan Xushan, Li Yanmin, et al. Spatio-temporal characteristics of extreme precipitation in the Ili River Basin based on CMIP6[J]. Arid Land Geography, 2025, 48(8): 1329-1341.]

[20] Han H, Gong D Y. Extreme climate events over northern China during the last 50 years[J]. Geographical Sciences, 2003, 13(4): 469-479.

[21] Wang Q, Zhai P, Zhang Q. Regional patterns of climate change and extreme events in China since 1961[J]. Journal of Meteorological Research, 2025, 39(3): 688-697.

[22] Zhai Panmao, Wang Cuicui, Li Wei. A review on observational studies of changes in precipitation extremes[J]. Climate Change Research, 2007, 3(3): 144-148. [Zhai Panmao, Wang Cuicui, Li Wei. A review on study of change in precipitation extremes[J]. Climate Change Research, 2007, 3(3): 144-148.]

[23] Leonard M, Westra S, Phatak A, et al. A compound event framework for understanding extreme impacts[J]. Wiley Interdisciplinary Reviews: Climate Change, 2014, 5(1): 113-128.

[24] McPhillips L E, Chang H, Chester M V, et al. Defining extreme events: A cross-disciplinary review[J]. Earth' s Future, 2018, 6(3): 441-455.

[25] Bezak N, Mikoš M. Changes in the compound drought and extreme heat occurrence in the 1961–2018 period at the European scale[J]. Water, 2020, 12(12): 3543, doi: 10.3390/w12123543.

[26] Kong Q Q, Guerreiro S B, Blenkinsop S, et al. Increases in summertime concurrent drought and heatwave in eastern China[J]. Weather and Climate Extremes, 2020, 28: 100242, doi: 10.1016/j.wace.2019.100242.

[27] Yu R, Zhai P M. Changes in compound drought and hot extreme events in summer over populated eastern China[J]. Weather and Climate Extremes, 2020, 30: 100295, doi: 10.1016/j.wace.2020.100295.

[28] Li H X, Sun B, Wang H J, et al. Characteristics and mechanisms of the severe compound cold-wet event in southern China during February 2022[J]. Environmental Research Letter, 2023, 18(11), 114021, doi: 10.1088/1748-9326/ad0163.

[29] Zhou Jing, Sun Yan, Qi Yajing. Interdecadal changes and cause analysis of spring compound extreme low-temperature and rainy events in China[J]. Climate Change Research, 2024, 20(1): 1-9. [Zhou

Jing, Sun Yan, Qi Yajing. Analysis on interdecadal variation and the causes of compound extreme cold and rainfall events in spring in China[J]. *Climate Change Research*, 2024, 20(1): 1-9.]

[30] Bai Zhaoye, Xu Guochang, Sun Xuejun, et al. *Weather over Northwest China*[M]. Beijing: Meteorological Press, 1991: 258-357. [Bai Zhaoye, Xu Guochang, Sun Xuejun, et al. *Weather over northwest China*[M]. Beijing: Meteorological Press, 1991: 258-357.]

[31] Tang Guoan, Yang Xin. *ArcGIS Geographic Information System Spatial Analysis Experiment Course* (2nd ed.)[M]. Beijing: Science Press, 2012: 289-292. [Tang Guoan, Yang Xin. *ArcGIS geographic information system spatial analysis experiment course* (2nd ed.)[M]. Beijing: Science Press, 2012: 289-292.]

[32] Wei Fengying. *Modern Climate Statistical Diagnosis and Prediction Technology* (2nd ed.)[M]. Beijing: Meteorological Press, 2007: 63-66. [Wei Fengying. *Modern climate statistical diagnosis and prediction technology* (2nd ed.)[M]. Beijing: Meteorological Press, 2007: 63-66.]

[33] Livezey R E, Chen W Y. Statistical field significance and its determination by Monte Carlo techniques[J]. *Monthly Weather Review*, 1983, 111(1): 46-59.

[34] Yu Rong, Zhai Panmao. New understanding and insights regarding compound extreme events[J]. *Transactions of Atmospheric Sciences*, 2021, 44(5): 645-649. [Yu Rong, Zhai Panmao. Advances in scientific understanding on compound extreme events[J]. *Transactions of Atmospheric Sciences*, 2021, 44(5): 645-649.]

[35] Yan Zhongwei, Yang Chi. Patterns of extreme climate change in China in recent decades[J]. *Climatic and Environmental Research*, 2000, 5(3): 267-272. [Yan Zhongwei, Yang Chi. Geographic patterns of extreme climate change in China during 1951-1997[J]. *Climatic and Environmental Research*, 2000, 5(3): 267-272.]

[36] Liu Mingchun, Zhang Qiang, Deng Zhenyong, et al. Influence of climate change on agricultural production in the Shiyang River Basin[J]. *Scientia Geographica Sinica*, 2009, 29(5): 727-732. [Liu Mingchun, Zhang Qiang, Deng Zhenyong, et al. Influence of climate warming on agricultural production in Shiyang River Basin[J]. *Scientia Geographica Sinica*, 2009, 29(5): 727-732.]

[37] Wang Runyuan, Zhang Qiang, Wang Yaolin, et al. Response of maize to climate warming in the arid region of Northwest China[J]. *Acta Botanica Sinica*, 2004, 46(12): 1387-1392. [Wang Runyuan, Zhang Qiang, Wang Yaolin, et al. Response of corn to climate warming in arid areas in northwest China[J]. *Acta Botanica Sinica*, 2004, 46(12): 1387-1392.]

[38] Sun Yang. Climate change and its impact on agricultural production in the arid region of Northwest China[D]. Beijing: Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, 2010. [Sun Yang. Climate change and its impact on the agricultural production in the arid region of northwest China[D]. Beijing: Institute of Geographic Sciences and Natural Resources Research, CAS, 2010.]

[39] Zhang Qiang, Deng Zhenyong, Zhao Yingdong, et al. Impacts of global climate change on agriculture in Northwest China[J]. *Acta Ecologica Sinica*, 2008, 28(3): 1210-1218. [Zhang Qiang, Deng Zhenyong, Zhao Yingdong, et al. The impacts of global climatic change on the agriculture in northwest China[J]. *Acta Ecologica Sinica*, 2008, 28(3): 1210-1218.]

Identification and change characteristics of compound low temperature and rainfall events of spring in the eastern Hexi Corridor

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Abstract: Compound low-temperature and rainfall (CTLR) events are among the complex, high-incidence climate extremes occurring in the eastern Hexi Corridor. They are important climate indicators and meteorological disasters that cause more severe damage to agricultural production and the ecological environment than single extreme climate events. Based on daily minimum temperature and precipitation data from five meteorological stations (spring of 1960—2024) in the eastern Hexi Corridor, CTLR events were identified and characterized via the percentile threshold method and the principle of maximum proximity. Spatiotemporal characteristics of CTLR events were subsequently analyzed using the inverse distance weighting interpolation and linear trend methods. The results show the following: (1) Springtime and March–May CTLR events in the region assumed distribution characteristics of more in the south, less in the north, ranked by frequency as Gulang>Tianzhu>Liangzhou>Yongchang>Minqin. High-frequency areas were clustered in the Gulang shallow mountainous area, whereas the Minqin desert area served as the low-frequency area. (2) Spring, as well as March and April CTLR events showed decadal and annual decreases, whereas May showed a nonmonotonic trend, increasing first before decreasing. Peak CTLR frequency years (spring and monthly) varied across regional and local scales, and CTLR absences were recorded in individual years. This provides an important scientific basis and practical reference for agricultural production and ecological security.

Keywords: identification; change characteristics; compound low temperature and rainfall events; percentile threshold method; Hexi Corridor