Likelihood of concurrent climate extremes and variations over China

Ping Zhou and Zhiyong Liu

1 Key Lab of Guangdong for Utilization of Remote Sensing and Geographical Information System, Guangzhou Institute of Geography, Guangzhou 510070, People’s Republic of China
2 School of Civil Engineering, Sun Yat-sen University, Guangzhou 510275, People’s Republic of China
3 Guangdong Engineering Technology Research Center of Water Security Regulation and Control for Southern China, Sun Yat-sen University, Guangzhou 510275, People’s Republic of China

E-mail: liuzhiy25@mail.sysu.edu.cn

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Abstract

Extreme climate events such as droughts and heat waves exert strong impacts on ecosystems and human well-being. Estimations of the risks of climate extremes typically focus on one variable in isolation. In this study, we present a method to examine the likelihood of concurrent extreme temperature and precipitation modes at the interannual scale, including compound cool/dry and cool/wet events during the cold season as well as compound hot/dry and hot/wet events during the warm season. A comparison of changes in the likelihood of such joint climate extremes was then conducted between the first (1961–1987) and second (1988–2014) halves of the full observed records. Our findings indicate a decrease in the occurrence probability for most concurrent modes over much of China, despite positive shifts found over southwestern and northeastern parts of China for the compound hot/dry events in the warm season. We further examined changes in likelihood related to these four compound climate extremes between the historical observed period (1961–2014) and the future period (2021–2080) based on climate model simulations with the RCP8.5 scenario. Our results show widespread increases in the occurrence probability for wintertime cool/dry and summertime hot/dry and hot/wet events over most parts of China but with different magnitudes, while much of China may experience declining likelihood of the wintertime cool/wet extremes in the future.

1. Introduction

Existing studies and the global change agenda have highlighted that global warming may increase the frequency, intensity, and spatial extent of extreme climate events globally, despite uncertainty at small spatial and temporal scales. This could have profound socioeconomic and environmental impacts (Smith 2011, Shih-Chieh and Ganguly Auroop 2011, Lloret et al 2012, IPCC 2013, Horton et al 2015). Global warming may also alter inherent characteristics of temperature, precipitation and other climate phenomena and increase the risk of climatic extremes (Seneviratne et al 2012).

In general, the definition of climate extremes in a large amount of literature refers to a value of a climate variable such as precipitation and temperature greater (or lower) than a threshold determined over a specified climate reference period or historical climatology (Seneviratne et al 2012). In addition, the combination of events that are not themselves extreme may lead to extreme impacts. Temperature and precipitation extremes are generally related to heat waves, cold snaps, ice storms, floods and droughts. Concerns about changes in extremes of temperature and precipitation have been widely raised over the past decades. Academic communities, decision-makers and public media have a widespread recognition of the consequences of climate extremes worldwide, which have had severe impacts on economic benefits, human health, and ecosystems (Katz and Brown 1992, Ciais et al 2005, Soussana et al 2010, Hong et al 2011, Houze et al 2011, Trenberth and Fasullo 2012). General results based on global analyses have shown widespread substantial increases in temperature extremes associated with warming (Alexander et al 2006).
Regional studies in China have concluded that the number of extreme high-temperature days had a sandwich-like spatial pattern, with strongly decreasing trends in central China and increasing trends in both northern and southern China (Wei and Chen 2009). Among the various regions of China, studies have revealed that the frequencies of low and high-temperature extremes are different (Qian and Qin 2006), and that the frequency and distribution of precipitation extremes had an even more complicated pattern (Zhai et al. 2005). Although the joint occurrence of extreme precipitation and temperature, such as the simultaneous occurrence of heat waves and drought (or precipitation deficit) is important, research has largely focused on the two phenomena independently. However, several recent studies have explored trends and changes in concurrent precipitation and temperature extremes and highlighted the importance of investigating joint events instead of isolated ones (Zhang et al. 2000, Beniston 2009, Estrella and Menzel 2012, Hao et al. 2013, AghaKouchak et al. 2014, Zscheischler and Seneviratne 2017).

Nevertheless, many studies have focused on traditional skills (e.g., frequency analysis and linear trend analysis) to examine the frequency and trends of concurrent climate extremes. The present work differs from such studies by modeling the probabilistic dependence of precipitation and temperature and thereby investigating the probabilities of climate extreme concurrence (i.e., the hazards). In addition, such evaluation can provide further information about whether the relative likelihoods of such joint climate extreme events were substantially altered over various periods. A change in probabilities of the hazards may directly impact the risk of concurrent climate extremes (Zscheischler and Seneviratne 2017).

In China, extreme climate events have exerted profound impacts on both human societies, natural environment and other industrial and agricultural sectors (Zhai et al. 2005, Sun and Ding 2010, Ye 2014, Xiao et al. 2016, Chen and Sun 2017). Over the past decades, a number of extreme climate events have caused large losses of life and tremendous economic losses. For instance, in 2013 summer, severe droughts affected the most populous and economically-developed part of China (i.e., Eastern China) and caused large economic and societal impacts with losses in excess of $0.8 billion. We restricted our geographic focus on the analysis of climate extremes in warm and cold seasons within China. In addition to the investigation of likelihood of climate extreme concurrence and spatial patterns across China, we also assessed whether there were discernible changes in likelihood of joint climate extremes between the first (1961–1987) and second (1988–2014) halves of the full observed records (1961–2014) and between the entire historical period 1961–2014 and a future period 2021–2080.

2. Data and methodology

A gridded monthly precipitation and temperature dataset (spatial resolution 0.5° × 0.5°) for China from 1961 to 2014 was obtained from the National Climatic Center of the China Meteorological Administration (http://cdc.cma.gov.cn/). This continuous gridded dataset was derived from station-based daily precipitation and temperature records from a total of 800 national meteorological stations across China. The quality and homogeneity of the climatic observations from these stations were checked and controlled by using the cumulative deviations test and the standard normal homogeneity test. More details of this gridded dataset are available from Xu et al. (2013) and Yin et al. (2015). The projected precipitation and temperature data for the next 60 years (2021–2080) were from the National Center for Atmospheric Research’s single-model ‘Large Ensemble Community Project’ (LENS), which consists of 40 simulations of the Community Earth System Model at 1° × 1° spatial resolution. LENS was forced in the IPCC AR5 RCP8.5 emissions pathway. This dataset is available from http://cesm.ucar.edu/projects/community-projects/LENS/. All 40 model runs were considered in this study and those runs were averaged before computing the occurrence probability. Prior to further analysis, we linearly detrended both the observational and modeled climate data in order to eliminate the climate change signal on long-term trends while climate change effects on trends in the dependence of climate variables are retained (Zscheischler and Seneviratne 2017).

First, we provide the definitions of climate extremes used in our study. Some studies (Beniston 2009, Hao et al. 2013) used 25% and 75% quantile thresholds to define extreme climate conditions. Following these previous studies, we used 25% and 75% quantile thresholds to define extreme precipitation and temperature in order to capture a large number of events. Although certain extreme climate thresholds are considered in the current study, it should be emphasized that any climate extremes of interest could be examined once the joint dependence of precipitation and temperature has been established. Therefore, we used four compound extreme modes: T25/P25, T25/P75, T75/P25 and T75/P75, indicating combinations of extreme cool/dry, cool/wet, hot/dry and hot/wet events, respectively. P75 (T75) indicates extreme high precipitation (temperature) events above the 75% quantile threshold, whereas P25 (T25) denotes precipitation (temperature) events below the 25% quantile threshold. In this study, we mainly focus on concurrent extreme hot/dry and hot/wet events in the warm season (June–August), and concurrent extreme cool/dry and cool/wet events in the cold season (December–February), producing one value per year for each of the warm or cold seasons (Zscheischler and Seneviratne 2017).
Table 1. Goodness-of-fit (chi-square) statistics and the corresponding p values of different theoretical distributions for temperature and precipitation in both summertime and wintertime over the full 54 year period at the selected location (113°37′15.95°E, 32°34′52.26′′N). Best-fitted distributions are shown in bold.

| Distributions | Summer temperature | Winter temperature | Summer precipitation | Winter precipitation |
|---------------|---------------------|--------------------|----------------------|----------------------|
|               | Chi-square   | p value | Chi-square | p value | Chi-square | p value | Chi-square | p value |
| Gaussian      | 6.643      | 0.354  | 3.849       | 0.697  | 7.326       | 0.291  | 8.533      | 0.201  |
| Gamma         | 6.664      | 0.353  | 3.872       | 0.693  | 3.717       | 0.760  | 9.848      | 0.131  |
| Lognormal     | 6.671      | 0.352  | 3.885       | 0.692  | 2.885       | 0.823  | 14.167     | 0.027  |
| Weibull       | 10.949     | 0.089  | 3.287       | 0.772  | 5.075       | 0.534  | 8.419      | 0.208  |

Given the defined quantile thresholds, we calculated the occurrence probability of joint extreme precipitation and temperature events corresponding to four joint modes. Regarding the T25/P25 mode, the joint probability distribution of temperature (denoted by X) and precipitation (denoted by Y), Pr(x, y), can be expressed as:

\[ \text{Pr}(X \leq x, Y \leq y) = C(F_X(x), F_Y(y)) = (u, v), \]  

where \( C \) is the copula function and its form reflects the joint cumulative distribution function, \( F_X(x) \) and \( F_Y(y) \) represent the marginal non-exceedance probability distribution of temperature and precipitation (\( u = F_X(x) \) and \( v = F_Y(y) \)).

For the T75/P75 mode, the joint probability is

\[ \text{Pr}(X > x, Y > y) = \hat{C}(u', v'), \]  

where \( u' \) and \( v' \) are exceedance probabilities of temperature and precipitation, i.e., \( u' = 1 - u \) and \( v' = 1 - v \), respectively, \( \hat{C} \) is the survival copula (Salvadori et al. 2013, AghaKouchak et al. 2014).

For the T75/P75 mode:

\[ \text{Pr}(X \leq x, Y > y) = u - C(u, v'), \]  

The joint probability of the T75/P25 mode is

\[ \text{Pr}(X > x, Y \leq y) = v - C(u', v). \]

Regarding the joint distribution method, it is noteworthy that our current analyses extend the applicability of copula by considering several compound climate extreme modes (e.g., T25/P75, T75/P25 modes), in addition to the compound hot and dry events analyzed by previous studies using copula and survival copula (Zscheischler and Seneviratne 2017, Zscheischler et al. 2017). Before modeling the joint probability distribution, we need to fit an appropriate marginal distribution for temperature and precipitation over individual periods considered. A set of theoretical probability distributions commonly-used in hydrometeorology were considered, e.g., Gaussian, gamma, Weibull, and lognormal. The maximum likelihood estimation was used to estimate the parameters of each distribution. The chi-square goodness-of-fit test was applied to determine the best-fit distribution (Gyasi-Agyei 2013, Liu et al. 2016, 2018). According to the chi-square goodness-of-fit test, the theoretical distribution with the smallest chi-square statistics indicates the best-fitted distribution.

To illustrate, we randomly selected precipitation and temperature data from a single location (113°37′15.95°E, 32°34′52.26′′N) in China. First, the appropriate marginal distributions of temperature and precipitation were determined by the chi-square goodness-of-fit test (chi-square statistics and \( p \) values), as shown in table 1. The chi-square test returns the \( p \) value, which should be greater than the significance level of \( \alpha \) (here, \( \alpha = 0.05 \)) (i.e., failing to reject the null hypothesis) (Snedecor and Cochran 1989, Khedun et al. 2014). The best-fitted distribution for each variable was determined by the smallest chi-square statistics and the \( p \) values greater than the defined significance level.

After marginal distributions of each variable were determined, we computed the four compound extreme modes by using equations (1)–(4), respectively. We considered several copula functions including Gumbel, Frank, Clayton, and Gaussian that have been widely used in hydrological and climatological applications (e.g., Salvadori and De Michele 2004, Bárdossy and Pegram 2013, Madadgar and Moradkhani 2013, Li et al. 2014, Hao and Singh 2016, Liu et al. 2015, 2016, Hao et al. 2017). We selected the appropriate bivariate copulas based on the Akaike information criterion (AIC) following Schepsmeier et al. (2015) and the best copulas were determined by the smallest AIC statistics. Regarding different historical periods (i.e., 1961–1987, 1988–2014, and 1961–2014) and future periods (i.e., 2021–2047, 2054–2080, and 2021–2080) based on the LENS projections, we independently determined new distributions and copula functions for temperature and precipitation and consistent approaches were used. We plotted maps of these joint distributions and probability values for the four joint climate modes at the randomly selected location (113°37′15.95°E, 32°34′52.26′′N), as shown in figure 1. To test the robustness of the copula-based method, we simply count the percentage of co-occurrences of four climate modes at the selected grid. Both approaches result in close results (figure 1).

3. Results and discussion

By applying the methods described above, we were able to quantitatively estimate the likelihood of the
The concurrence of different extreme temperature and precipitation events at the interannual scale (including cold and warm seasons) over China. These analyses were carried out for the full 54 year period and the first and last 27 year periods. Figure 2 maps spatial patterns of the likelihood of the four joint climate extreme modes over China based on the full 54 year records. The results show that the probability of occurring joint climate extremes varies markedly across the country (it is worth noting that the expected probability is always $0.25 \times 0.25 = 6.25\%$ in the case of independence of temperature and precipitation). For the joint cool/dry mode in the cold season, the occurrence probability below 5% spans a large geographic region and encompasses most of China (figure 2(a)). Some locations in the eastern part of the country had higher probabilities. For the extreme cool/wet events during wintertime (figure 2(b)), higher occurrence probability can be identified over the country compared with the cool/dry mode across the country. Under this mode, the likelihood in the southwestern, northwestern and northeastern parts of the country is higher than the other parts, where occurrence probability is generally above 20%. Such patterns also indicate that during the cold season the chance of occurring joint cold/wet extremes is generally higher than that of joint cold/dry extremes over the country. During the warm season, as shown in figure 2(c), the likelihood of compound hot/dry extremes in most parts of the country is greater than 15%, particularly over 20% in some regions of southern and northern parts. In most of China, with the exception of the Qinghai-Tibetan Plateau (figure 2(d)), the compound hot/wet events in summertime are very unlikely to occur (probability less than 5%). In addition, we also analyzed the correlations between temperature and precipitation for both cold and warm seasons during 1961–2014 (figure S1 in the supplementary material is available online at stacks.iop.org/ERL/13/094023/mmedia). It can be observed that the likelihood of compound climate events in the areas with stronger correlations (either positive or negative) is

![Figure 1](https://example.com/fig1.png)

**Figure 1.** Joint return periods and the likelihood values (the white triangles) computed by copula-based approach (in white text) and simple counting (in green text) for concurrent cool/dry (a) and cool/wet (b) modes during the cold season (December, January and February), as well as hot/dry (c) and hot/wet (d) modes during the warm season (June, July and August) at the selected location (113°37'15.95″E, 32°34'52.26″N). Climate data were linearly detrended before further analysis.
Figure 2. Likelihood of concurrent cool/dry (a) and cool/wet (b) modes during the cold season, as well as hot/dry (c) and hot/wet (d) modes during the warm season over China based on the full 54 year (1961–2014) observations. Climate data were linearly detrended before further analysis.

Figure 3. Differences in likelihood between 1961–1987 and 1988–2014 (Likelihood_{second} − Likelihood_{first}) for joint cool/dry (a) and cool/wet (b) modes during the cold season, as well as hot/dry (c) and hot/wet (d) modes during the warm season. Climate data were linearly detrended before further analysis.
generally higher than the areas with lower correlation coefficients (or uncorrelated). This indicates that the correlations between the two climate variables have a direct effect on the occurrence probability of concurrent climate events.

We performed similar analyses for the first and last 27 year sub-periods individually, which enabled comparison of changes in the likelihood of concurrent climate extremes over the two periods (results from the second half of the record minus those from the first). Figure 3 shows changes in the likelihood (Likelihood\textsubscript{second} − Likelihood\textsubscript{first}) of the two sub-periods (the individual likelihood maps for each sub-period are shown in figures S2, S3). There were declining chances of concurrent cool/dry extremes during the cold season over most of the country (figure 3(a)). There were some locations (mainly in the Qinghai-Tibetan Plateau), showing an increasing likelihood. For the cool/wet mode during the cold season (figure 3(b)), there were negative shifts in likelihood across the country. The decrease in likelihood greater than 15% occurs mainly in most parts of Qinghai-Tibet Plateau and Northwest China. Figure 3(c) shows both negative and positive shifts in likelihood across the country. Increased occurrence probability of joint hot/wet events during the warm season appears mainly in southwestern and northeastern China, with some areas indicating increasing likelihood above 15%. Areas of decrease are mainly located in southeastern and western parts of the country. As illustrated in figure 3(d), the decreased likelihood of joint hot/wet extremes embraces a large areal coverage. Some regions in central and northeastern parts of China experienced an increased likelihood of occurrence of such joint extremes.

We further explored the changes in likelihood related to these four compound climate events between 1961–2014 (observed data) and 2021–2080 (LENS simulations), as illustrated in figure 4. To assess the reliability of the LENS simulations, we compared the likelihood of four compound events produced by averaged climate data over the 40 LENS runs as shown in figure 5 (maps of the compound occurrence probability generated by the 10th and 90th quantiles of the 40 LENS runs are also provided as a comparison in figures S5, S6) with that generated by the observed climate data in the historical period (1961, 2014) (i.e., figure 2). Broad similarities can be identified although some differences exist, in terms of the magnitudes in likelihood values and spatial patterns. Figure 4(a) shows that, during the cold season, areas of increased likelihood of the concurrent cool/dry events may cover over most of China except for the northern part and the middle and lower Yangtze River Basin in the future. For the joint cool/wet condition in the cold season (figure 4(b)), the distribution of

![Figure 4](image-url)
decreased occurrence probability spreads across most of the country. In some regions of Northeast China, Northwest China, Qinghai-Tibet Plateau and Inner Mongolia, there are comparatively larger negative shifts, while the North China Plain shows slightly increased occurrence probability. We also analyzed the changes in the likelihood of the joint hot and dry extremes between 1961–2014 and 2021–2080 during the warm season. For the compound hot/dry extremes (figure 4(c)), the increased likelihood appears over a substantial part of the country. Also, the likelihood pattern in figure 4(c) shows some regions (e.g., the middle and lower Yangtze River Basin) shifted with the decreased probability. Figure 4(d) shows that the area of increased probability of compound hot/wet events covers over almost all of the country for the summertime hot/wet mode. Additionally, despite the large uncertainty in the likelihood patterns generated from the LENS simulations (e.g., figures S5 and S6 for the 10th and 90th quantiles of the 40 LENS runs, respectively), the likelihood patterns produced by averaged climate data over the 40 LENS runs (figure S4) appear broadly consistent with the results generated from the observed data for the period 1961–2014 (figure 2). We also provided the maps of changes in likelihood between 1961–2014 and 2021–2080 calculated by averaged LENS simulations (figure S7) and broad consistency could be identified as compared to figure 4.

As illustrated in figure 5, we also demonstrate the mean values (±standard deviations) of the likelihood of different concurrent climate extremes averaged over four different geographical divisions with similar climatology (figure S8). Four different sub-periods with the same length (i.e., 27 years) were involved in the comparison, i.e., 1961–1987, 1988–2014, 2021–2047 and 2054–2080. According to the mean values, only the Qinghai-Tibet division shows a positive shift in likelihood between 1961–1987 and 1988–2014 for the joint cool/dry mode (figure 5(a)). However, Qinghai-Tibet division shows larger variations in the likelihood of occurring joint cool/dry extremes than other divisions according to the standard deviations. All divisions present negative shifts between 1961–1987 and 1988–2014 for the joint cool/wet mode during the cold season with respect to the mean values (figure 5(b)). Most divisions except for North China division present negative changes in likelihood between 1961–1987 and 1988–2014 for the compound summertime hot/wet extremes (figure 5(c)). Only Qinghai-Tibet division experienced a negative shift in the likelihood of the hot/wet extremes between the first two sub-periods based on spatially averaged values (figure 5(d)). Most divisions tend to experience higher occurrence probability for both cool/dry and cool/wet modes by comparing the future sub-periods with the historical sub-period 1988–2014 (figures 5(a), (b)). Between the two future sub-periods, the four divisions present an increasing trend in likelihood for the cool/dry mode but a declining trend for the cool/wet mode. For the two summertime climate modes, all divisions present an increasing trend in likelihood between the two future sub-periods (figures 5(c), (d)).

The variations in occurrence probability of climate extremes could be influenced by multiple factors.
(Horton et al. 2015, Wang et al. 2015). Since we have detrended the climate data before further analysis, the detected changes in occurrence probability for the compound cool/dry and cool/wet modes may mainly be related to the changes in dependence structure of temperature and precipitation instead of the long-term trends in the two variables. To illustrate this, we show the interannual correlations between temperature and precipitation for both wintertime and summertime over the first (1961–1987) and second (1988–2014) halves of the full observations (figure S9). The spatial patterns of the changes in correlations may explain the variations in the probability of different compound events (figures 3 and 5). For instance, we see much of western China experienced a decreased probability of occurring cool/wet events in the wintertime, which corresponds well with the decrease in negative correlations between temperature and precipitation over these areas (figures S9(a), (b)). In the summertime, the likelihood of occurring compound hot/dry events is increased in the eastern part of Inner Mongolia while the likelihood of occurring compound hot/wet events is decreased. This is mainly due to the intensification of negative correlations in these regions (figures S8(c), (d)). Moreover, the weakened negative correlations in Northwest China and the middle and lower Yangtze River Basin could be responsible for the decreased occurrence likelihood of the hot/dry events. The increased likelihood of the hot/wet events in the southern part of Northwest China relates to intensified positive correlations between the two variables in the summertime. For the future periods, increased likelihood of the cool/dry events can be found over most of the country while decreased occurrence probability of the cool/wet events appears to dominate over China in the wintertime (figures 4, 5). The occurrence probability of both hot/dry and hot/wet events in the summertime tends to increase over most of the country in the future, which could be largely related to variations in the strength of the dependence between temperature and precipitation under the future climate change.

The large-scale climate signals could also be related to the changes in concurrent climate extremes. For instance, it has been widely reported that the climate variations in much of China are linked to the El Niño–Southern Oscillation (ENSO) (Wu et al. 2010, Feng et al. 2011). Based on the Oceanic Niño Index (Kousky and Higgins 2007), we made a simple comparison and found that the number of El Niño and La Niña events which could intensify the climate extremes is quite different between the two observed periods, e.g., seven (seven) moderate and strong La Niña (El Niño) events in 1988–2014 and only three (five) La Niña (El Niño) events in 1961–1987. Moreover, many existing studies also documented that land-atmosphere feedbacks within the climate system may play an important role in the development of compound climate extremes and could either lead to damping (negative feedbacks) or enhancing (positive feedbacks) the climate extremes (Seneviratne et al. 2012, Zscheischler and Seneviratne 2017). In addition to natural forcings, Sun et al. (2014) have also examined the strong contributions to the occurrence of climate extremes from the rapid urbanization associated with economic and population development over the past 30 years.

The above results rely on the appropriate fitting of marginal distributions and copula functions for individual variables and joint dependence. For each pixel, the best-fitted margins and copula functions were chosen among several candidates. This evokes a discussion of examining the geographical variation of the best-fitted marginal distribution for precipitation and temperature. Such an investigation enables us to evaluate the performance of different theoretical distributions over various regions of China. To illustrate this, we used an example of precipitation and temperature data during the cold season. Figures S10(a) and (b) show the best-fitted marginal distributions determined by the chi-square statistics and p value for precipitation and temperature during the cold season based on the full 54 year records, respectively. For most of the country, the best-fitted distribution among the four distributions is the normal distribution for precipitation and lognormal distribution for temperature. Additionally, figure S10(c) maps spatial patterns of the corresponding best-fitted copula functions at each pixel based on the AIC scheme. The Gaussian and Joe copulas seem to be dominant over most of China.

Given that we independently fitted the appropriate marginal distributions and copula functions for temperature and precipitation over different sub-periods, we also analyzed to what extent different marginal distributions and copula functions may affect the likelihood estimation. To illustrate this, we again examined the changes in the likelihood of the four concurrent climate extremes between the first and last 27 year sub-periods of the full observation records. However, when fitting the temperature and precipitation data during the second sub-period, we used the marginal distribution and copula functions determined by the first sub-period. A comparison of these analyses (figure S11) with the above results (figure 3) shows broad similarities but also some differences regarding the magnitudes in likelihood differences and spatial patterns. This suggests the necessity of fitting the best appropriate marginal distribution and copulas for individual datasets or sub-periods when performing probability-based analyses.

4. Conclusions

The likelihood of temperature and precipitation extremes was broadly investigated for two phenomena in isolation. We examined the joint dependence of
precipitation and temperature and further evaluated the likelihood of joint occurrence of climate extremes during the cold and warm seasons over China. We presented a copula-based model of joint exceedance or non-exceedance probabilities to estimate the likelihood of various compound extreme modes, i.e., cool/dry and cool/wet events during the cold season, as well as hot/dry and hot/wet events during the warm season. First, we used this method to identify the likelihood of these joint climate extremes in China for the period 1961–2014 and delineated the spatial patterns. We then compared the changes in likelihood of the joint climate extremes between the first (1961–1987) and second (1988–2014) halves of the full observed records. Despite strong spatial variability, general patterns were detected and a decrease in the occurrence probability for most concurrent modes can be found in most of China. Some regions showed declines in probability above 15%. However, we also found increased occurrence probability along southwestern and northeastern parts of China for the compound hot/dry events in the warm season. In addition, using the climate model simulations forced in the IPCC AR5 RCP8.5 emissions pathway, we evaluated the differences in likelihood related to these four joint climate extreme modes between 1961–2014 and 2021–2080. For the cool/dry mode in the cold season, increased occurrence probability may occur across most of China. More cool/dry extremes in the future may have strong influences on the agro-pastoral systems and cause large economic losses and societal impacts over these areas. The results also indicate lower probability of concurrent cool/wet events over arid and semiarid zones of China (e.g., Inner Mongolia, Northwest China and Qinghai-Tibet Plateau) in the future. Positive shifts in likelihood may also appear in much of the country for the summertime hot/dry mode. Regarding extreme hot/wet events, a widespread increase may also occur over almost all of China in the future based on our analyses. Moreover, this study also discussed the geographical variation of the best-fitted marginal distributions and copula functions for the precipitation and temperature over China.

The present study underlines the need for identifying the likelihood of various compound extreme events in China and presents a copula-based method for such an investigation. Our analyses mapped with clear spatial patterns may provide insights to decision-makers in evaluating the possibility of joint climate extreme occurrence in China. However, our analyses were solely on monthly scales. Definitions of climate or weather extremes can vary with timescale, e.g., sub-daily, daily, seasonal, and annual. Future work will extend the current study to different time scales.

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ORCID iDs

Zhiyong Liu https://orcid.org/0000-0002-6930-5879

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