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Research papers

Impact of dependence changes on the likelihood of hot extremes under drought conditions in the United States

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ABSTRACT

The conditional dependence between droughts and hot extremes in many regions tends to lead to compound dry and hot extremes that may cause serious impacts on the ecosystem, human society and infrastructure. Thus, it is of particular importance to understand variations of the conditional dependence between droughts and hot extremes under global warming. We investigated changes in the dependence between droughts (characterized by the Standardized Precipitation Index, SPI) and hot extremes (characterized by extreme temperature) during summer for two periods 1949–1979 and 1980–2010 in the United States. The copula method was employed to construct the conditional distribution of hot extremes under drought conditions to show changed likelihoods of hot extremes. Results demonstrated increased negative dependence between droughts and hot extremes in large regions in the western, southern and northeastern U.S., leading to a higher likelihood of hot extremes conditional on droughts from the first period 1949–1979 to the recent period 1980–2010. Meanwhile, decreased negative dependence between droughts and hot extremes was shown in parts of Midwest and southeastern U.S., leading to a decreased likelihood of hot extremes conditional on droughts. Due to disastrous impacts of both droughts and hot extremes, our findings will aid mitigation efforts of extremes in the U.S. in a warmer climate.

1. Introduction

Global warming has been shown to lead to increased frequency and intensity of weather and climate extremes (e.g., drought, heat wave) in many regions (Mishra and Singh, 2010; Dai, 2013; Horton et al., 2016; Huang et al., 2017). In recent decades, concerns have been raised on concurrent or consecutive occurrences of multiple extremes (i.e., compound extremes) that may pose stronger threats to the society and ecosystems than individual extremes, such as the 2003 heat wave in Europe and 2010 heat wave in Russia that were accompanied by droughts (Seneviratne et al., 2012; Leonard et al., 2014; Wahl et al., 2015; Hao et al., 2018). Empirical work using observations and model simulations has shown an increase in the frequency and spatial extent of compound drought and hot extremes in a warming climate at regional and global scales (Hao et al., 2013; Mazdiyasni and AghaKouchak, 2015; Zscheischler and Seneviratne, 2017). It is thus important to understand the occurrence and variations of compound droughts and hot extremes.

The association between precipitation and temperature at different time scales has been evaluated (Trenberth and Shea, 2005; Adler et al., 2008; Herath et al., 2018; Sharma and Mujumdar, 2019). Studies have shown the existence of negative dependence between precipitation and temperature during summer season in regions including the U.S. and Europe, which tends to result in a tendency of dry and hot summer and high likelihood of compound droughts and hot extremes (Koster et al., 2009; Zscheischler and Seneviratne, 2017; Zhou and Liu, 2018; Chen et al., 2019). Evidence from both observational and modeling products illustrates that one of the main drivers of the negative dependence is the soil moisture-temperature feedback, especially in the transitional regions of wet and dry climate (Hirschi et al., 2011; Mueller and Seneviratne, 2012; Greve et al., 2014; Gallego-Elvira et al., 2016; Holmes et al., 2017). Specifically, soil moisture deficit reduces evaporation and leads to increased sensible heat, causing localized increase in temperature, which is predominately strong in regimes that are neither moisture nor energy limited and can occur throughout the year (Hirschi et al., 2011; Miralles et al., 2018). This conditional dependence of hot extremes under drought conditions has been shown to be an important feature of the occurrence of compound droughts and hot

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extremes (Seneviratne et al., 2012).

The soil moisture-temperature feedback and potential increase of extremes under climate change play important roles in controlling current and future changes of regional temperature (Quesada et al., 2012; Berg et al., 2016; Lorenz et al., 2016; Vogel et al., 2017; Miralles et al., 2018). Recent studies have shown that climate change may lead to shifts in the "hotspots" of soil moisture-temperature feedback (Dirmeyer et al., 2013; Whan et al., 2015). For example, using the correlation coefficient as a metric of land–atmosphere coupling, previous studies have shown many processes in the soil moisture-temperature feedback may be significantly modified under climate change (Seneviratne et al., 2010; Berg and Sheffield, 2018; Vogel et al., 2018; Berg and Sheffield, 2019). This is expected to affect the conditional dependence between droughts and hot extremes. However, assessing the likelihood of variations of hot extremes under drought conditions due to changes in the conditional dependences is rather rare.

In this study, we investigate changes in the conditional likelihood of hot extremes under drought conditions during the period 1949–2010 in the United States. The copula-based conditional distribution model is employed to estimate the likelihood of hot extremes under drought conditions incorporating changes in the dependence for two periods 1949–1979 and 1980–2010. We first show the changes in the dependence between droughts and hot extremes during summer in the United States. We then quantify changes in the likelihood of hot extremes under drought conditions during the two periods using the copula method.

2. Methods

The copula methodology (Nelsen, 2006), which has been widely used in modeling dependence between hydroclimatic variables (Genest and Favre, 2007; Fang et al., 2019; Zhao et al., 2019), was employed in this study to construct the joint/conditional distribution of droughts and hot extremes (Zscheischler and Seneviratne, 2017; Ribeiro et al., 2019). For continuous random variables X (droughts) and Y (hot extremes) with marginal probability distributions U and V, the joint probability (or the likelihood of compound droughts and hot extremes) can be expressed with a Copula C as (Nelsen, 2006):

$$P(X \le x, Y > y) = u - C(u, v) \tag{1}$$

A variety of copula families, such as the elliptical and Archimedean, have been employed for constructing the joint distribution shown in Eq. (1). Three 2-parameter copulas, including Clayton, Gumbel, and Frank, are among the most commonly used copulas for the bivariate case (Kao and Govindaraju, 2010) and were used in this study for modeling the joint distribution of droughts and hot extremes. A suitable copula for each period was selected based on the Akaike Information Criterion (AIC) (Akaike, 1974), an estimator of the relative quality of the model, and the best model was the one with the minimum AIC value (Zhang and Singh, 2007).

The conditional probability of hot extremes higher than a certain threshold given drought conditions lower than or equal to a certain threshold can be expressed as following (Hao et al., 2017):

$$\mathrm{P}_{Y>y|X\leqslant x} = \frac{P(X \leqslant x, Y > y)}{P(X \leqslant x)} = \frac{u - C(u, v)}{u} \tag{2}$$

The conditional probability in Eq. (2) quantifies the impact of droughts on the likelihood of hot extremes. Note that the numerator (i.e., $u - C(u,v)$) is essentially the likelihood of compound dry and hot extremes.

3. Data and results

3.1. Data

Monthly precipitation and daily maximum temperature (T_{max}) data in the U.S. at 1/8 degree resolution were used in this study (Maurer et al., 2002), which is available for the period from 1949 to 2010. These data were separated into two equal periods 1949–1979 and 1980–2010 for comparisons of results (31 years for each period). The joint distribution of droughts and hot extremes is constructed based on the relatively long record of each period to assess changes in the likelihood of hot extremes under drought conditions. The Standardized Precipitation Index (SPI) (McKee, 1993), based on accumulated precipitation of different time scales, is used as the drought indicator in this study. To avoid uncertainties that may arise in the fitting of parametric distributions, we computed the SPI by using the empirical Gringorten plotting position formula (Gringorten, 1963) to estimate the marginal distribution.

Since droughts and hot extremes may lead to large impacts to the water supply and energy consumption in summer, we focus on the summer season of June, July, and August (JJA). For the drought condition, we computed the 3-month SPI based on accumulated precipitation of JJA to represent drought conditions during summer. The summertime SPI was computed for the two 31-yr periods (1949–1979 and 1980–2010) separately. The threshold -0.8 was used to characterize the drought condition, which has been used to classify the moderate drought condition in U.S. Drought Monitor (USDM) (Svoboda et al., 2002). For the hot extreme, we identified the highest daily maximum temperature for each month during JJA, respectively, and then averaged them to represent the extreme temperature (T_x) during summer. The 90th percentile of extreme temperature has been commonly used to define the hot extreme (Perkins and Alexander, 2013; Whan et al., 2015) and was also employed in this study. We also used different thresholds to define droughts (SPI ≤ -0.5) and hot extremes (e.g., $T_x >$ 70th and $T_x >$ 80th) and results were generally consistent (not shown).

3.2. Dependence between droughts and hot extremes

We first assess the dependence between droughts and hot extremes for the first period 1949–1979, which will then be compared with that for the period 1980–2010 to show the dependence change. The Kendall rank correlation coefficient (τ), which is a nonparametric measure of the dependence (Genest and Favre, 2007; Zhang and Singh, 2007; Wahl et al., 2015), between the SPI and percentiles of T_x was computed for the period 1949–1979, as shown in Fig. 1. Compared to limited regions with positive dependence in the western U.S., the negative correlation coefficient τ for the period 1949–1979 was shown for most regions in the United States with strong dependence in large regions of central and southeastern U.S, consistent with previous studies (Koster et al., 2009; Ford et al., 2017). The negative correlation between droughts and hot extremes in large regions of the U.S. implies that the drought-induced warming may, in turn, exacerbate the drought condition (Mueller and Seneviratne, 2012), resulting in compound droughts and hot extremes (Seneviratne et al., 2012; Zscheischler and Seneviratne, 2017). In this study, we are particularly interested in the drought-induced warming

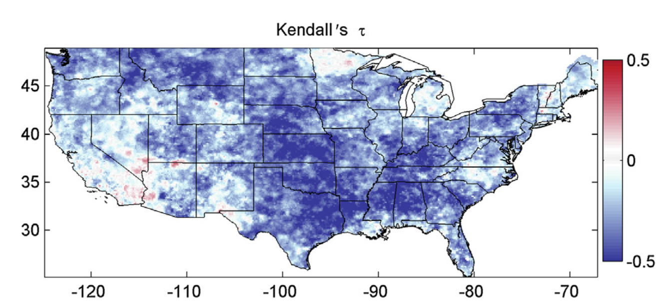

Fig. 1. Kendall rank correlation coefficient (Kendall's τ) between the Standardized Precipitation Index (SPI) and percentile of temperature during summer (June, July, and August, JJA) of the period 1949–1979 in the U.S.

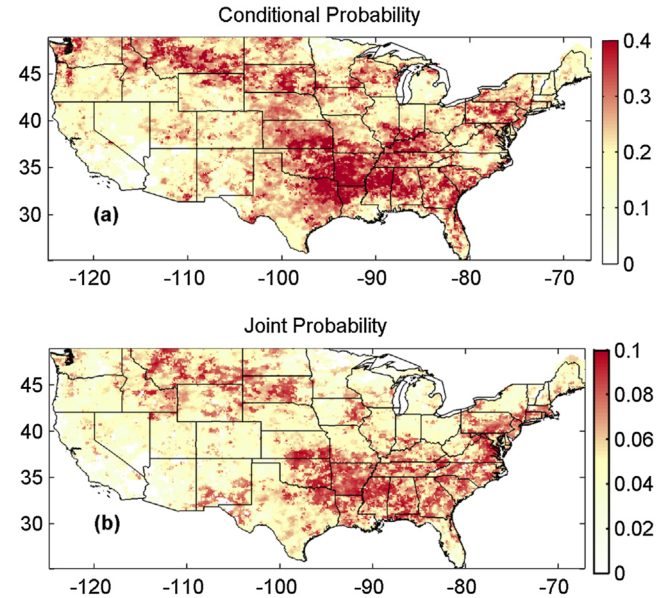

Fig. 2. The conditional probability of extreme temperature higher than 90th percentile given SPI ≤ −0.8 (i.e., P($T > Tx_{90}$|SPI ≤ −0.8)) during summer for 1949–1979 in the U.S. (a) and the joint probability of the compound dry and hot extreme P($T > Tx_{90}$, SPI ≤ −0.8) (b).

and we focus on the region with negative dependence in Fig. 1.

3.3. Conditional likelihood of hot extremes under droughts

To assess the likelihood of hot extremes associated with drought-induced warming, we focus on the conditional behavior of hot extremes under drought conditions. The copula model was used to estimate the conditional probability of hot extremes given droughts (Section 2). At each grid point, the three copulas (Frank, Clayton, and Gumbel) were first fitted to drought and hot extreme indicators (SPI and T_x) for the period 1949–1979 and the best copula was selected based on minimum AIC values.

The conditional probability of extreme temperature (T_x) higher than the 90th percentile given the SPI lower than or equal to −0.8 (i.e., P ($T > T_{x90}$|SPI ≤ −0.8)) during summer for the period 1949–1979 is shown in Fig. 2(a). Given drought conditions, the conditional probability of hot extremes is high in regions with significant negative dependence. If droughts and hot extremes are independent, the conditional probability of temperature higher than the 90th percentile would be 0.1. From Fig. 2(a), the conditional probability of hot extremes given drought SPI ≤ −0.8 was higher than that of the independence case. In addition, the likelihood of the compound dry and hot extreme is also higher in regions with significant negative dependence (Fig. 2(b)). This result highlights the critical importance to study hot extremes from a multivariate perspective taking into account drought conditions (or the compound dry and hot extreme), especially in regions with significant correlation coefficients between the two extremes.

To assess potential uncertainties from the choice of different thresholds, we also use the threshold SPI ≤ −0.5 and T_x > 70th to show the joint and conditional probability in Eqs. (1) and (2), respectively (Supplementary materials Fig. S1). The pattern of the higher conditional probability (and joint probability) in regions with significant negative dependence between droughts and hot extremes (Fig. S1) is consistent with results in Fig. 2, indicating the overall robustness of the results. To evaluate the performance of the copula model, we also compute the conditional probability (and joint probability) using the empirical method (Supplementary materials Fig. S2), which is conducted based on the R package "CompoundEvents" currently under development (https://r-forge.r-project.org/projects/compoundevents/

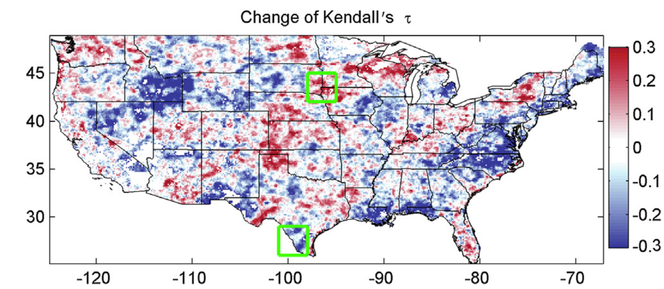

Fig. 3. Changes of the Kendall rank correlation for the two periods 1949–1979 and 1980–2010 for regions with negative correlations during 1949–1979. Two selected regions are also marked in this Figure (region A: 101W–98°W, 26N–29°N, region B: 98W–95°W, 42N–45°N).

). The empirical conditional probability can be estimated by counting the relative frequency of seasons with T_x > 70th for all seasons with SPI ≤ −0.5. The conditional probability of hot extremes conditional on droughts from the copula model and from the empirical method are generally in agreement with each other. For example, the conditional probability in eastern Texas is around 0.6 (Fig. S1), similar to the value shown from the empirical estimation (Fig. S2). These results demonstrate the satisfactory performance of the copula model.

3.4. Changes in the dependence

The difference of Kendall rank correlation coefficient τ between droughts and hot extremes for the two periods 1949–1979 and 1980–2010 is shown in Fig. 3. For the regions with negative dependence during 1949–1979, the decrease of the correlation coefficient τ (or increase of the negative dependence) was mainly shown in the western, southern, and northeastern regions. The increase of negative correlation coefficient (or the decrease of negative dependence) was shown in some areas of Midwest and southeastern US. To clearly show this pattern of dependence changes, we selected two regions (region A: 101W–98°W, 26 N–29°N, region B: 98 W–95°W, 36 N–39°N) with increased and decreased negative dependence, respectively. The boxplot of the correlation coefficient τ for all grids during the two periods in the two regions is shown in Fig. 4(a) and (b), respectively. For region A, the median of the correlation coefficient τ was −0.23 during 1949–1979 and it decreased to −0.39 during 1979–2010. For region B, the median of the correlation coefficient was −0.32 during 1949–1979, which increased to −0.21 during 1979–2010. The change of the dependence between droughts and hot extremes may be caused by potential variations of the soil moisture-temperature interaction for the two periods under global warming (Seneviratne et al., 2010; Zscheischler and Seneviratne, 2017). These results indicate the dependence between droughts and hot extremes for the period 1979–2010 has changed compared with that for 1949–1979 in these two regions.

3.5. Likelihood changes associated with dependence changes

Based on the analysis of the dependence between the two extremes (Section 3.2) and the associated likelihood of hot extremes under drought conditions (Section 3.3), the change in the dependence shown in Fig. 3 (Section 3.4) is expected to result in changes in the likelihood of hot extremes under drought conditions. We then compared the conditional probability of hot extremes given droughts (i.e., SPI ≤ −0.8) during summer for the two periods 1949–1979 and 1980–2010 to assess changes in the likelihood of hot extremes under drought conditions based on the copula model. To avoid uncertainties from the copula differences during the two periods, the same type of copula for the period 1949–1979 was used for the period 1980–2010 (but with different copula parameters).

For negatively correlated droughts and hot extremes, if the negative

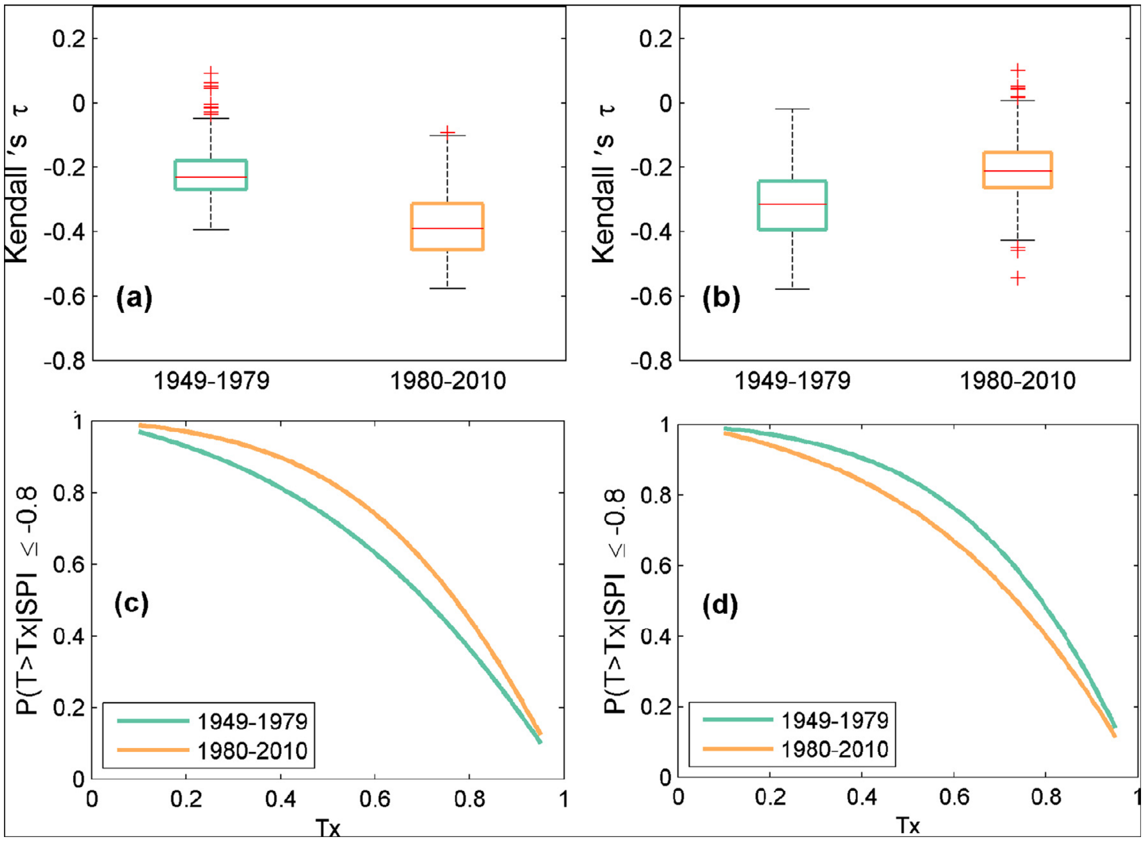

Fig. 4. Change in the dependence and impacts on the conditional probability of hot extremes under drought conditions for two selected regions (region A: 101W–98°W, 26N–29°N, region B: 98W–95°W, 42 N–45°N). (a, b) Boxplots of correlations between the SPI and extreme temperature (T_x) during the two periods for region A and B, respectively. (c, d) Conditional probability $P(T > Tx\,|SPI \le -0.8)$ for the two periods 1949–1979 and 1980–2010 in the two regions.

correlation coefficient τ decreases (i.e., increased negative dependence), the likelihood of the occurrence of hot extremes is expected to be higher given the same drought condition, indicating a higher chance of occurrences of compound dry and hot events. To clearly show the pattern of changes in the likelihood, we took the average of precipitation and temperature of all grids in the two regions (regions A and B), from which the indicators of droughts and hot extremes were computed to assess regional changes in the likelihood associated with dependence changes. The conditional probability $P(T > T_x|SPI \le -0.8)$ for the two periods in these two regions is shown in Fig. 4(c, d). Due to the increased negative dependence between the SPI and T_x for region A, the conditional probability $P(T > Tx_{90}|SPI \le -0.8)$ increased from 0.22 to 0.28. Due to the decreased negative dependence between the SPI and T_x for region B, the conditional probability $P(T > Tx_{90}|SPI \le -0.8)$ decreased from 0.27 to 0.22. These results demonstrate changes of likelihoods of hot extremes associated with changes in the dependence between droughts and hot extremes.

The ratio of the likelihood, which is defined as the conditional probability $P(T > Tx_{90}|SPI \le -0.8)$ for 1980–2010 divided by that for 1949–1979 is shown in Fig. 5(a). The conditional probability $P(T > Tx_{90}|SPI \le -0.8)$ for the period 1980–2010 showed an increase in the regions with increased negative dependence, such as the southern U.S. (Fig. 3). Overall the ratio of likelihood increased significantly (around 1.5 to 2 folds) for the second period (1980–2010) in the western, southern and northeastern U.S.. This indicated that with the same drought condition (i.e., $SPI \le -0.8$), the occurrence of hot extremes increased by 150% to 200% in these regions during 1980–2010. The increased likelihood of hot extremes was also reflected in the increased joint probability of $SPI \le -0.8$ and $T > Tx_{90}$ for 1980–2010 than that for 1949–1979, as shown in Fig. 5(b). Note that these results are consistent with the previous study on the frequency of compound drought

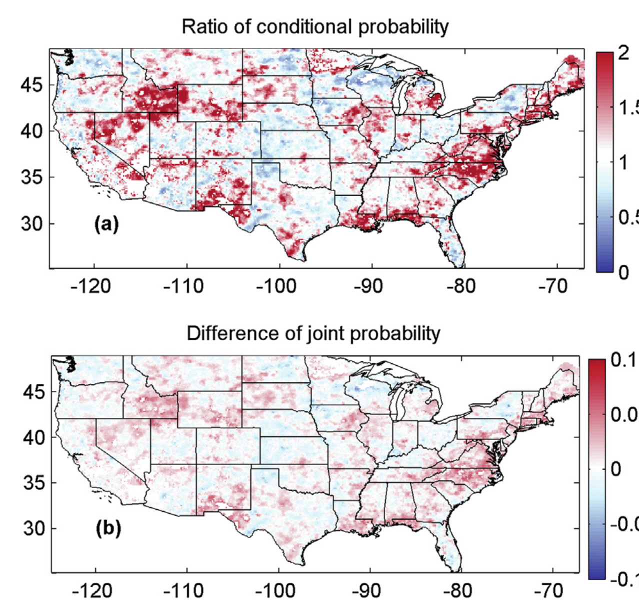

Fig. 5. The ratio of conditional probability $P(T > Tx\,|SPI \le -0.8)$ for the two periods 1949–1979 and 1980–2010 (a) and the difference of joint probability $P(SPI \le -0.8,\ T > Tx)$ for the two periods (b).

and heat waves in the U.S. based on the empirical approach (Mazdiyasni and AghaKouchak, 2015), which shows the increased frequency in roughly similar regions. Overall, given the same drought condition, the likelihood of hot extremes (and compound droughts and hot extremes) is shown to increase in the western, southern and northeastern U.S. due to the increased negative dependence between droughts and hot extremes. For the regions with decreased negative dependence, a decreased conditional probability of hot extremes given SPI ≤ -0.8 (and likelihood of compound droughts and hot extremes) was observed accordingly.

4. Conclusions and discussions

This study investigated changes in the likelihood of hot extremes under drought conditions for the two periods 1949–1979 and 1980–2010 in the United States. Results showed that dependence between droughts and hot extremes in the U.S. has changed with regional differences, resulting in changes in the likelihood of hot extremes under drought conditions (and compound droughts and hot extremes). Specifically, the negative dependence between droughts and hot extremes in large regions in western, southern and northeastern U.S. has increased, while that in certain Midwest and southeastern regions has decreased. The increased negative dependence from the first period 1949–1979 to the second period 1980–2010 was associated with increased likelihood of hot extremes under drought conditions, while the decreased negative dependence was associated with decreased likelihood of hot extremes under drought conditions.

Totally 31 data pairs of the SPI and extreme temperature were used for the statistical inference of the dependence evaluation and multivariate modeling for the two periods 1949–1979 and 1980–2010. The data limitation in this regard may induce certain uncertainties in the evaluation of the dependence change and associated likelihood of hot extremes. In addition, the selection of copula models in the statistical analysis may also be affected by relatively short records, which may lead to uncertainties in the probability estimation. Moreover, the significance of changes in the dependence and associated likelihood were not assessed. These are the caveats in interpreting results of this study. We conducted statistical analysis of the likelihood of extremes based on the stationary concept. Results from this study have shown the changed correlation coefficient between droughts and hot extremes, which indicates the nonstationary property of the dependence. Due to important role of dependence in the risk analysis of multivariate or compound extremes, a nonstationary-based risk assessment framework can also be employed to investigate the likelihood of hot extremes and compound droughts and hot extremes (Bender et al., 2014; Jiang et al., 2015; Kwon and Lall, 2016; Sarhadi et al., 2018), which will be conducted in our future studies. Based on the changed pattern of hot extremes conditioned on droughts, it is expected that regions with increased negative dependence between droughts and hot extremes are expected to be particularly vulnerable to a warmer climate under the influence of natural and anthropogenic forcing. This calls for improved mitigation efforts in coping with droughts and heat extremes in these regions. Considering disastrous impacts of (compound) droughts and hot extremes, this study highlights the importance of assessing the likelihood of droughts and hot extremes from a multivariate perspective.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2019.124410.

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