Dry-hot magnitude index: a joint indicator for compound event analysis

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Abstract
Weather and climate extremes, such as droughts and heat waves, have been commonly characterized by different properties, including frequency, duration, and magnitude. The magnitude is among the most important properties that determine the impact of extremes. Compound dry and hot events may cause detrimental impacts on water resources, energy security, crop production and food security, and have been receiving increasing attention in recent years. Although extensive studies have been conducted to investigate the magnitude of individual droughts or hot extremes, evaluation of the magnitude of compound dry and hot events has received limited attention. In this study, we develop a dry-hot magnitude index (DHMI) to characterize the magnitude of compound dry and hot events, using monthly precipitation and daily maximum temperature, which takes into account both dry and hot conditions. The DHMI is used to analyze the spatial and temporal patterns of the magnitude of compound dry and hot events in China during summer (June, July, and August) for the period of 1961–2013. Results show that high magnitudes of compound dry and hot events mainly occur in northeastern and southwestern China, with higher magnitudes mostly observed in recent decades since the 1990s. The proposed magnitude index has potential to be a useful tool for analyzing compound dry and hot events and their impacts.

1. Introduction
For decades, severe droughts and hot extremes have struck the society and ecosystem in different regions around the globe, and have caused destructive impacts, including river ecosystem degradation, crop yield reduction, or even famine (e.g. 2010–2011 East Africa drought) (Dai 2011, Funk 2011, Cournou and Rahmstorf 2012, van Dijk et al 2013). For example, among all billion-dollar events that occurred in the US during the 1980–2011 period, the damages from droughts/heatwaves were around 210.1 billion dollars (Smith and Katz 2013). Under global warming, more frequent, more severe, and longer droughts as well as hotter and longer heat wave events have been observed in many regions worldwide and are projected to intensify in the future (Meehl and Tebaldi 2004, Fischer and Schär 2010, Dai 2012, Perkins et al 2012, Trenberth et al 2014, Leng et al 2016, Russo et al 2017, You et al 2017). The adverse impacts of droughts or hot extremes and increased risks in the future call for improved efforts to evaluate changes in different properties and their impacts on the ecosystem and society under a changing climate.

Drought is generally defined as the prolonged deficit of precipitation and can be classified into different types, including meteorological, agricultural, hydrological, and socioeconomical drought. Different drought indicators have been developed to monitor the drought condition of different types, such as the decile, Standardized Precipitation Index (SPI) (McKee et al 1993), Palmer Drought Severity Index (PDSI), among others (Mishra and Singh 2010). The SPI can be used to assess drought conditions at different time scales and has been recommended as the indicator to track the meteorological drought by the World
Meteorological Organization (WMO) (Hayes et al. 2011). However, the disadvantage of SPI is that it is only based on precipitation and may thus fall short in characterizing complicated drought phenomenon. To address this issue, a variety of composite drought indicators have been developed recently for characterizing the complex drought phenomenon. To incorporate precipitation and potential evapotranspiration, which is particularly useful for drought assessments under global warming.

Drought has been commonly characterized by different properties, including duration, frequency, intensity, and magnitude. For a specific indicator, these drought properties can be extracted using the run theory developed by Yevjevich (1967), in which the series is partitioned into different sequences based on a threshold level and then different concepts of run (e.g. the distance between successive downcrosses and upcrosses can be regarded as duration) can be used to describe drought properties. A large number of severe drought events in many regions across the globe with different durations and severities/intensities have been analyzed in recent decades (Dai 2011, Trenberth et al. 2014), such as the 2011 Texas drought, 2012–2016 California drought, and 2001–2009 millennium drought in southeast Australia (van Dijk et al. 2013). The 2011 drought in Texas was unprecedented in intensity (Nielsen-Gammon 2012). The California’s 5 year drought during 2012–2016 was identified as one of the longest and most exceptional droughts with tremendous losses of agriculture and ecosystems (Lund et al. 2018). A number of studies have been devoted to modeling these drought properties using multivariate analysis (Shiau 2006, Xu et al. 2015). For instance, Shiau (2006) constructed a multivariate distribution function based on two-dimensional copulas by joining drought duration with severity. These studies generally reveal the importance of investigating multiple properties, rather than focusing on frequency alone, for better understanding of droughts and their impacts.

In addition, severe hot extremes have occurred frequently in recent years and caused disastrous impacts on human health, water supply, food security, and economic development (Luterbacher et al. 2004, Barriopedro et al. 2011, Perkins 2015). High and positive temperature anomalies have been commonly used to characterize heat-related extremes, either based on an absolute threshold (e.g. higher than 35°C) or a relative threshold (e.g. higher than 90th percentile of daily maximum temperature of local climatology). To address the potential limitation of the absolute threshold for comparison across seasons or regions, the relative threshold based on percentiles has been commonly used, which defines the occurrence of extreme events based on the exceedance (or nonexceedance) of a threshold relative to local conditions. For example, the heat wave is commonly defined as the case when temperature is higher than a high threshold of daily maximum temperature for a period of consecutive days (e.g. 3 d) (Meehl and Tebaldi 2004, Perkins and Alexander 2013, Zampieri et al. 2017). Typical examples include the 2003 European heatwave and the 2010 Russian heatwave, which were identified as the most severe heat wave events on record (Barriopedro et al. 2011, Miralles et al. 2014, Russo et al. 2015, Russo et al. 2017).

A variety of indices have been developed to characterize the frequency and duration of temperature extremes or heat waves, such as the Heat Wave Duration Index and Warm Spell Duration Index (Schön et al. 2002, Alexander et al. 2006). Fischer and Schär (2010) suggested a methodology for studying multiple aspects of extreme temperature (or heat wave) based on daily maximum temperature, including heatwave day frequency, heatwave day number, heatwave maximum duration, and heatwave amplitude, which can be applied to different heat wave indices. For example, on the Excess Heat Factor (EHF) (Nairn and Fawcett 2013), Perkins and Alexander (2013) adopted a similar methodology to investigate the frequency, number, duration, amplitude, and magnitude of heat extremes in Australia by defining the heat wave based on the 90th percentile for both maximum temperature (Tx90) and minimum temperature (Tn90). Apart from the progress in characterizing different aspects of heat waves/temperature extremes, efforts have been made to measure the combined properties to distinguish different extreme events (e.g. two heat waves with the same duration but different temperature anomalies). Russo et al. (2014) proposed a heat wave magnitude index (HWMI), which was defined based on an empirical probability distribution function of the sum of three highest consecutive daily maximum temperatures of each year, to assess the magnitude of heat wave by combining duration and intensity. As the HWMI has limitations in assigning the magnitude to very high temperature, Russo et al. (2015) proposed the heat wave magnitude index daily (HWMI-d) that addressed the limitation by assigning the daily magnitude with values in $[0, +\infty]$ instead of a bounded interval $[0, 1]$. These developments of metrics of hot extremes have provided effective tools to improve our understanding of heat-related events and their influences.

Previous studies mostly evaluated different properties of droughts and hot events in isolation. Recent decades have witnessed a suite of compound dry and hot events, such as the 2003 heatwave in Europe and the 2010 heatwave in Russia that were characterized by concurrent droughts (Sedlmeier et al. 2017). Numerous studies have shown severe impacts of compound dry and hot events on agricultural production, ecosystems, and human society (Seneviratne et al. 2012, Zampieri et al. 2017, Zscheischler et al. 2018). For
example, the 2003 dry and hot extreme in Europe led to the death of around 70 000 people (Barriopedro et al. 2011). Most of the recent developments on analyzing compound events focused on the frequency or spatial extent (Hao et al. 2013, Mazdiyasni and Agha-Kouchak 2015, Sharma and Mujumdar 2017, Wu et al. 2019). The actual impact of a compound event is not only associated with its occurrence but also with the magnitude of both drought and hot extreme (e.g. the impact of extremes with the same drought condition but different positive temperature anomalies is expected to be different). However, assessments of the magnitude of compound dry and hot events have been lacking and a suitable magnitude measure is therefore desirable.

The objective of this study therefore is to develop a joint index to characterize the magnitude of compound dry and hot events. The proposed index was then applied for analyzing the spatial and temporal patterns of compound dry and hot events that occurred in China during summer (June, July, and August (JJA)) for the period of 1961–2013. The development of the index for the magnitude of compound dry and hot events is presented in section 2. Application of the index for the evaluation of historical compound dry and hot events in China is illustrated in section 3, followed by the conclusion in section 4.

2. Method

The magnitude of a drought can be roughly defined based on the difference between the drought indicator (DI) value and a threshold during drought months (denoted as $\Delta DI$), with a large departure from the threshold indicating a high magnitude of the drought (Yevjevich 1967, Nam et al. 2015). The magnitude of a hot extreme can be characterized by the temperature (e.g. daily maximum temperature $T_{\text{max}}$) above a specific threshold (denoted as $\Delta T$) (Perkins and Alexander 2013, Russo et al. 2014). It is challenging to combine the two different quantities directly to develop a magnitude index of compound dry-hot events due to the difference in their units and the resulting index would be hard to interpret. Following Russo et al. (2014), we transformed $\Delta T$ by fitting a marginal distribution to obtain its nonexceedance probability $P(\Delta T)$, which falls within $[0, 1]$, with a large $\Delta T$ corresponding to a high probability $P(\Delta T)$. Accordingly, the DI is defined as the probability (or percentile) of the accumulated variable of interest (not transformed to standard normal variates as in the traditional way to compute SPI or SPEI) (Russo et al. 2013), which also ranges from 0 to 1.

The dry-hot magnitude index (DHMI) of compound dry and hot events can then be defined as (illustrated in figure 1):

$$\text{DHMI} = \sum_{m=1}^{M} \left[ \frac{1}{P(\Delta T_m)} \frac{\Delta DI_m}{\sum_{m=1}^{M} \Delta DI_m} \right],$$

where $M$ is the number of periods (e.g. months or seasons) to define the DHMI; $\Delta DI_m$ is the number of days for the period $m$ with daily $T_{\text{max}}$ higher than the threshold; $\Delta T_m$ is the difference between daily $T_{\text{max}}$ and the threshold for the day $d_m$ (during which $T_{\text{max}}$ is higher than the threshold); $P(\Delta T_m)$ is the marginal distribution function of $\Delta T$ for each period $m$, which can be fitted to $\Delta T_m$ of the whole climatology based on a nonparametric distribution, such as Weibull plotting position formula; and $\Delta DI_m$ is the difference between drought indicator DI and the corresponding threshold for the period $m$. Note that $\Delta DI_m$ is zero when the corresponding DI value $(D_{I_m})$ is higher than the threshold $(D_I)$. Specifically, $\Delta DI_m$ is computed as:

$$\Delta DI_m = \begin{cases} D_{I_m} - D_I, & \text{if } D_{I_m} < D_I, \\ 0, & \text{if } D_{I_m} > D_I. \end{cases}$$

Note that there are various indicator options for droughts and hot events that one can choose from when assembling an index. Different indicators (e.g. SPI, PDSI, SPEI) can be used to define DI. In addition, the index can be computed for different periods (e.g. month, season or year) by choosing different values of parameter $M$ and the unit of period $m$. If parameter $M = 1$ and the unit of $m$ is month, then the index DHMI is computed for a single month (e.g. August) of each year. Similarly, if parameter $M = 3$ and the unit of $m$ is month, then the index DHMI can be computed for three months (e.g. JJA), as illustrated in figure 1. The $\Delta T$ value in equation (1) can be defined for all days with temperature higher than the threshold during the period $M$ (as illustrated in figure 1). It can also be defined for each heat wave and only the days during each heat wave are accounted for in defining $\Delta T$ in this equation. This index DHMI can be viewed as the summation of drought magnitudes $\Delta DI_m$ weighted by the temperature nonexceedance probability $P(\Delta T_m)$ for each period $m$. Thus, the value of the DHMI ranges from 0 to the maximum value of $\Delta DI$ (for $M = 1$). For example, if the SPI is used as the meteorological drought indicator and the 30th percentile (corresponding to SPI value of $-0.5$) is selected as the threshold to define drought for a single period, then the DHMI ranges from 0 to 0.3.

3. Data and results

3.1. Data

We used monthly precipitation and daily $T_{\text{max}}$ data during JJA from 1961 to 2013 over China to calculate the magnitude of compound dry and hot events. These gridded data at a spatial resolution $0.5^\circ \times 0.5^\circ$ were obtained from the National Climatic Center of China.
Meteorological Administration (http://data.cma.cn/), which integrates observation data from 2472 meteorological stations across the whole nation. Monthly precipitation data were used to compute the drought indicator and the daily $T_{\text{max}}$ data were used to characterize hot conditions.

The SPI was selected as the drought indicator to define $D_{\text{I}}$, since it was recommended to track the meteorological drought by the WMO (Hayes et al 2011). The SPI can be computed based on the accumulation of precipitation of different time scales, which is fitted to a distribution function to obtain the marginal probability that is then transformed to a standardized index based on the standard normal distribution. In this study, the SPI based on the accumulated precipitation during JJA was used to characterize the drought condition during summer. An empirical method based on the Weibull plotting position formula was employed to compute the SPI (Stagge et al 2015). Note that we computed the nonexceedance probability of the accumulated precipitation during JJA (or transform the corresponding SPI to the uniform distribution) and used it as $D_{\text{I}}$ to compute the DHMI in equation (1).

3.2. Computation of DHMI

In this study, a compound dry and hot event occurs when daily $T_{\text{max}}$ is higher than the threshold during the dry summer. The drought occurrence during the summer season is defined as the percentile of the accumulated precipitation of JJA lower than the 30th percentile (corresponding to SPI $<-0.5$), which is used to define the abnormally dry condition in the US Drought Monitor (Svoboda et al 2002). This threshold was selected to obtain a relatively large number of records of compound events. Another potential consideration of this threshold was that the compound impact may result from an individual event without being extreme (Seneviratne et al 2012). In addition, we chose the 90th percentile of daily $T_{\text{max}}$, which has been commonly used as the threshold to define heat waves or temperature extremes (Alexander et al 2006, Perkins and Alexander 2013, Zampieri et al 2018), based on the records of daily maximum temperature in JJA of the full study period (i.e. all days with $T_{\text{max}}$ higher than the threshold during the drought season were used to define the DHMI). The justification for selecting this threshold was based on the balance of ‘extreme’ and ‘measurable’, since a higher threshold (e.g. 95th or 99th) for $T_{\text{max}}$ may result in very few events being measured, while a smaller threshold (e.g. 80th or 85th) may result in too many events being measured (Perkins and Alexander 2013).

3.3. Illustration of DHMI at one grid point

An illustration of the evolution of compound dry and hot events during JJA is shown in this section. We first selected one grid point (106°75'E, 29°25'N) located in Chongqing Municipality (one region with hot summer and frequent drought) in southwest China to illustrate the application of the DHMI for evaluating the magnitude of compound dry and hot events. We first calculated $\Delta D_{\text{I}}$ based on the difference between $D_{\text{I}}$ and the threshold 0.3 (for $D_{\text{I}}$ lower than the threshold) for each summer. In addition, $\Delta T$ was computed based on the summation of absolute values.

Figure 1. Illustration of the definition of the DHMI during summer JJA based on drought indicator ($D_{\text{I}}$) and daily maximum temperature ($T_{\text{max}}$). The black solid lines $D_{\text{I}0}$ and $T_{\text{B}}$ are the thresholds of $D_{\text{I}}$ and daily $T_{\text{max}}$, respectively. The blue line is $D_{\text{I}}$ series, and the red curve is the daily $T_{\text{max}}$. $\Delta D_{\text{I}1}$, $\Delta D_{\text{I}2}$ and $\Delta D_{\text{I}0}$ are the absolute values of the difference of the $D_{\text{I}}$ with the threshold ($\Delta D_{\text{I}} = 0$ of $D_{\text{I}} > D_{\text{I}0}$) for the corresponding month. $\Delta T_{n}$ is the absolute value of the difference of daily $T_{\text{max}}$ with the threshold (for $T_{\text{max}}$ higher than the threshold) for the day $i$.
of the difference of daily $T_{\text{max}}$ with the corresponding threshold (for daily $T_{\text{max}}$ higher than the threshold) for each summer of each year, from which $P(\Delta T)$ for the period 1961–2013 was obtained. The DHMI was then computed based on equation (1). The series of $\Delta DI$, $P(\Delta T)$ and the DHMI for each summer of the whole period 1961–2013 for the selected grid point are shown in figure 2. Overall, the DHMI was larger when both $\Delta DI$ and $P(\Delta T)$ were larger. For certain periods, such as the year 1972, although $P(\Delta T)$ was relatively high, the DHMI was still relatively low due to the low $\Delta DI$ in this period. These results indicate the basic property of the DHMI in incorporating both drought and hot conditions.

As shown in figure 2, the value of DHMI in 2006 was the largest for the whole period 1961–2013 (DHMI = 0.28), indicating that the magnitude of the compound dry and hot event in 2006 was the highest in the historical record for this grid point, followed by the dry and hot condition in 2011 (DHMI = 0.25). This extreme has been partly shown in previous studies with severe droughts and hot days in Chongqing Municipality in these two periods (Lu et al 2013, Wang et al 2014a, Chen et al 2017). Additionally, there were some other compound dry and hot events, such as the events in 1971 ($\Delta DI = 0.23$, $P(\Delta T)=0.78$) and 1992 ($\Delta DI = 0.19$, $P(\Delta T) = 0.93$). Compared with the compound event in 1992, the dry-hot event in 1971 presented a higher $\Delta DI$ and a lower $P(\Delta T)$. Thus, it is difficult to compare the magnitude of these two compound events by the individual $\Delta DI$ or $P(\Delta T)$. However, the proposed index DHMI overcomes this problem by integrating dry and hot conditions. Specifically, the values of the DHMI for the two summer periods 1971 and 1992 were 0.18 and 0.17 for this grid point, respectively. This indicates that the magnitude of the compound dry and hot event in 1971 was higher than that in 1992.

### 3.4. Compound dry and hot event during 2006 in southwest China

The southwest region of China, which has complex topography, is prone to extremely dry and hot summers (Ma et al 2017). During the extreme drought in the summer of 2006, Sichuan–Chongqing area was also struck by an extreme heat condition. According to statistics, the drought with hot condition in southwest China during JJA of 2006 caused at least 18 million people to experience water shortage and a 11.74 billion CNY of direct economic losses (Li et al 2011, Wang et al 2015). These impacts posed a serious threat to human health and socio-economic development.

Here, we chose the compound dry and hot event during JJA 2006 in this region as a case study to investigate its magnitude for illustrative purposes. As shown in figure 3(a), the Sichuan–Chongqing area experienced a severe drought and hot condition in 2006, with the DHMI values higher than 0.2 in most areas. The magnitude of compound events of this region during JJA for the whole study period of 1961–2013 was then computed to show its temporal variations. Here we took the spatial average of the DHMI values for all grids in the Sichuan–Chongqing area to obtain one value for each summer season. For JJA of each year, the SPI and $T_{\text{max}}$ anomaly ($T$-anomaly) were also computed and are shown for comparison (figure 3(b)). Severe compound events, such as those during 1997, 2006 and 2011, are seen from this figure, during which relatively low SPI and high $T_{\text{max}}$ anomaly were observed. The magnitude of the compound event for the period of JJA 2006 was the highest (with a DHMI value 0.19) among all these compound events. These results generally indicate the suitability of this
3.5. Spatial distribution of the magnitude

The average magnitude and maximum magnitude of compound dry and hot events over China during JJA for the period of 1961–2013 are shown in figures 4(a) and (b), respectively. Higher average magnitudes of compound dry and hot events (higher values of DHMI) mainly occurred in northeastern and southwestern China (figure 4(a)). These results are partly consistent with previous studies for severe droughts as well as heat waves occurring in these regions (Yu et al 2014, Wang et al 2017). For the eastern part of Inner Mongolia (northeastern China), Sichuan province and Chongqing Municipality (southwestern China), the high magnitude of the compound dry and hot event is generally in agreement with the high chance of concurrent dry and hot events in previous studies (Zhou and Liu 2018, Wu et al 2019). In addition, the maximum magnitude of the compound dry-hot event was relatively high in northeastern, eastern, central, and southern China (figure 4(b)).

There are several mechanisms that may contribute to the spatial pattern of magnitudes of compound dry and hot events in China. Due to the land–atmosphere interaction, the dry condition may amplify the surface temperature during summer, especially in the transitional regions of dry and wet climate (Koster et al 2009, Seneviratne et al 2010, Mueller and Seneviratne 2012). This may result in the heat wave (or consecutive days of exceptionally high temperature), which may, in turn, exaggerate the drought condition. From the definition of the DHMI in equation (1), this process is expected to lead to the higher magnitudes of extremes. Thus, the high magnitude of a compound dry and hot event during summer in northeastern and southwestern China may be related to the land atmosphere feedback (Hao et al 2017, Liu et al 2017). For example, Hao et al (2017) showed the interaction of droughts and hot extremes in these regions, which tended to result in a higher probability of concurrent dry and hot conditions and was expected to contribute to the high magnitude of compound dry and hot event. In addition, the large scale atmospheric circulation (e.g. Western Pacific Subtropical High (WPSH)) and sea surface temperature (SST) anomalies (e.g. El Niño Southern Oscillation) may also contribute to the high
magnitude of compound events through the influence on the occurrence of heat wave and/or drought in China (Wu et al. 2019). For example, the precipitation (or drought) over southwest China is commonly regulated by persistent SST anomalies and atmospheric conditions (Wang et al. 2015) and the Indian Ocean SST anomalies have been shown to contribute to the high temperature extremes over south China during summer (Hu et al. 2012). As another example, possible causes of the severe compound dry and hot event during 2006 in southwest China include the strengthening of the WPSH with the subtropical ridge shifting northward and westward, and the Tibetan high ridge moving eastward (Li et al. 2011, Wang et al. 2015). Other factors, such as rapid urbanization, may also play an important role in the concurrent climate extremes (Zhou and Liu 2018). Detailed exploration of the physical mechanisms of the high magnitude of compound dry and hot events is beyond the scope of this study and will be conducted in the future.

3.6. Temporal distribution of the magnitude
To evaluate temporal variations of the magnitude of compound dry and hot events, the year with the maximum magnitude of compound events (i.e. the highest value of DHMI) during JJA for the period of 1961–2013 over China was extracted, as shown in figure 4(c). Most high magnitudes of compound dry and hot events across the nation occurred in recent years after the 1990s. This is likely related to the previous findings of more severe droughts as well as more frequent hot days in more areas over China since the 1990s (Ding et al. 2009, Wang et al. 2012, 2017, Yu et al. 2014, You et al. 2017). These variabilities of droughts and hot extremes may also result from the warming climate, which causes increased frequency as well as increased severity of precipitation and temperature related extremes (Zhai and Pan 2003, Dai 2011, Wang et al. 2012, You et al. 2017). Note that northwestern China and the lower reaches of the Yangtze River are the two main regions where the highest magnitude of compound events occurred before the 1990s. This may be partly related to the significantly increased precipitation (Zhai et al. 2005, Lu et al. 2014) as well as decreased temperature (or heat wave events) (Wang et al. 2014b, You et al. 2017) in summer in these areas. These results indicate an increase in the risk of compound dry and hot events in many regions across China in recent years.

4. Conclusion
In this study, the DHMI was proposed based on monthly precipitation and daily maximum temperature for characterizing the magnitude of compound dry and hot events. The compound dry and hot event during 2006 in the southwest region of China was used as a case study to evaluate the performance of the
proposed index for analyzing properties of the compound event. The index was then applied to analyze the spatial and temporal distribution of the magnitude of compound dry and hot events during JJA for the period 1961–2013 in China. It was found that higher magnitudes of compound dry and hot events were mostly identified in northeastern and southwestern China. In addition, compound events with higher magnitudes tended to occur in recent decades after the 1990s across China.

The proposed DHMI enables the integration of different properties of both droughts and hot extremes and thus is expected to aid the quantitative evaluation of compound events and associated impacts. There are also some limitations of this index that may induce some uncertainties. The proposed index is mainly developed for the compound dry and hot conditions and the current formulation is not applicable for other compound events, such as the combined condition of wet and heat stress. In addition, this index is only defined based on daily maximum temperature with focus on the accumulated temperature above certain thresholds. Though $T_{\text{max}}$ has been widely used as an indicator for characterizing hot extremes, it has long been known that the minimum night-time temperature ($T_{\text{min}}$) also plays an important role in multi-day heat extremes and thus some indices (like EHF) opt to use $T_{\text{mean}}$ to incorporate daily $T_{\text{max}}$ and $T_{\text{min}}$ (Perkins and Alexander 2013). Moreover, though the index incorporates both dry and hot conditions, its performance in explaining extreme impacts (e.g. crop yield loss in different regions (Zampieri et al 2017)) should be further validated. Traditionally, it has been recommended that a drought indicator, such as SPI, should be computed based on at least 30 years of data. This is the minimum requirement of data length in computing the DHMI, since it is defined based on the concurrence of droughts and hot extremes. The extension and evaluation of the proposed index will be addressed in our future work. Note that our purpose of this study is not to replace other commonly used heat indicators but provide an alternative way to characterize compound extremes incorporating both dry and hot conditions. Many studies have shown that the increase of compound dry and hot extremes may occur in the future in many regions globally (Zscheischler and Seneviratne 2017, Zscheischler et al 2018), which may result in increased impacts on different sectors of the society and environment. The proposed magnitude index may contribute to the assessment of future impacts of compound events for formulating strategies to reduce their negative impacts.

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