Amplified intensity and duration of heatwaves by concurrent droughts in China

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Abstract:

Compound hot-dry climate extremes could lead to severer natural disasters and socio-economic impacts compared to individual events. An improved understanding of historical heatwave-drought compounds and their difference compared to heatwaves alone is needed for better predicting the occurrence and impacts of extremes under a changing climate. In this study, we investigated spatiotemporal variations of heatwave-drought compounds using meteorological data from more than 2,000 stations in China during 1980-2017, and compared the heatwave intensity and duration in heatwave-drought compounds with that in heatwaves alone. The annual occurrence frequency of heatwave-drought compounds increased significantly during 1980-2017. At the national level, heatwave intensity in heatwave-drought compounds was 34.24℃±4.39℃, which was higher than that in the heatwaves alone 33.33℃±4.35℃. The occurrence of long-lasting (duration > 7 days) heatwaves accounted for about 34.42% - 50.70% in heatwave-drought compounds, while this ratio was only 11.82% -21.55% in heatwaves alone. The quantitative evaluation of heatwave-drought compounds and heatwaves alone in China highlighted the amplified heatwave severity and duration in heatwave-drought compound extremes versus that in heatwaves alone.

Key words: heatwave-drought compound, heatwave alone, extremes, China

1 Introduction

Extreme weather and climate events have been widely studied over past decades, and there is a general agreement that extreme climate events will increase and have more profound impacts on Earth system in the future (Easterling et al., 2000; Zscheischler et al., 2018). Meanwhile, studies are emerging in compound extremes which are combination of multiple extreme climate events (Seneviratne et al., 2012; AghaKouchak et al., 2014; Zhou and Liu, 2018; Mukherjee et al., 2020). A suite of heatwave and drought compounds have been witnessed in recent decades, such as the 2003 European heatwave and 2010 Russian heatwave which were identified as typical heatwave and drought compounds (Ciais et al., 2005; Barriopedro et al., 2011; Sedlmeier et al 2017). Heatwave and drought compounds usually lead to sever impacts on agricultural production, ecosystems, and human society (Seneviratne 2012, Zampieri et al 2017, Zscheischler et al 2018). For example, the 2003 heatwave and drought compounds in Europe led to billions of dollars in economic losses and thousands of losses in lives (Barriopedro et al 2011). Considering disastrous impacts of heatwave and drought compounds and their potential increase under climate change, a systematic evaluation of their variations is needed for adaptation and mitigation strategies.

Droughts and heatwaves are two of the most important climate hazards around the world with profound impacts on human society and ecosystem (Easterling et al., 2000; Ciais et al., 2005), and they have been intensively studied as individual extremes in China (Sun et al., 2017; Liao et al., 2018). Droughts are associated with prolonged periods of precipitation shortage and can be grouped into three types including meteorological drought, agricultural drought and hydrological drought (Esfahanian et al., 2017). Due to their high frequency and tremendous damage, several drought indices have been developed to monitor and evaluate drought variabilities, such as the Standardized Precipitation Index (SPI) (McKee et al., 1993), Palmer Drought Severity Index

(PDSI) (Palmer, 1965) and Standardized Precipitation-Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2009). The SPI can be used to assess drought conditions at different time scales and has been recommended as the indicator to capture the meteorological drought by the World Meteorological Organization (WMO) (Hayes et al 2011). Based on SPI and SPEI indices, it was found that drought increasing mainly in South and Southwestern China during 1994 to 2013 (Wang et al., 2019). Meanwhile, with global warming, the occurrence of heat related extremes has been shown to increase at both regional and global scales (Seneviratne et al., 2014; Sun et al., 2014). A heatwave is regarded as a prolonged period of hot weather, spanning several days to several weeks, and can cause severe damage to human society and natural ecosystem, with impacts on human health (Dunne et al., 2011; Meehl and Tebaldi, 2004), crop production (Ciais et al., 2005) and energy demand (Flores-Larsen et al., 2021). Absolute criterion which applies a fixed temperature value is used to define heatwaves, such as 35°C recommended by the China Meteorological Administration (CMA), 32°C recommended by the WMO, etc. To improve applicability across different climatic regions fixed absolute thresholds have been replaced with locally defined thresholds in the form of high quantiles of the local temperature (Schoetter et al., 2015), and to allow warm periods away from high summer to be included, calendar-day based percentiles have been employed (Russo et al., 2014). For example, the heatwave 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 days) (Meehl and Tebaldi 2004, Perkins and Alexander 2013, Zampieri et al 2017).

At the global scale, several recent investigations based on historical records have demonstrated the variation in heatwave and drought compounds mainly in terms of their frequency and spatial extent, and an increase was detected in most parts of the world (Hao et al., 2013;

Zscheischler and Seneviratne, 2017; Sarhadi et al., 2018). China has a complicated and diverse climate, making its economic and social development vulnerable to the impacts of climatic extremes. Recently, a multitude of studies have been devoted to the variations of heatwave and drought compounds in China (Hao et al., 2015; Wu et al., 2019; Yu et al., 2020; Kong et al., 2020). Overlooking this compounding effect may lead to underestimate of heatwave intensity and its impacts. Despite previous studies on concurrent droughts and heatwaves, there are still a lack of quantitative studies investigating the difference between heatwave-drought compounds and heatwaves alone. Given more impactful of heatwave-drought compounds than individual heatwave or drought, what is the difference in intensity and duration between heatwave-drought compounds versus heatwaves alone and how the difference varies in different climate regimes are poorly understood.

Considering the disastrous impacts of heatwave-drought compounds and the need for an improved understanding of heatwave in growing compound events under a changing climate, using more than 2,000 meteorological observations, we evaluated spatial and temporal changes in heatwave-drought compounds and quantified the differences of heatwave intensity and duration between heatwave-drought compounds and heatwaves alone in China. The remainder of this paper describes in detail the datasets and methodology (Section 2), results (Section 3), discussion (Section 4), and conclusions (Section 5) for this study.

2 Data and Methodology

2.1 Data

Meteorological data from 2,474 national stations were collected from the China Meteorological Data Service Center (http://data.cma.cn/) from 1980 to 2017. In each year, data in five months from May to September were included to analyze extremes. Daily surface air temperature data measured at 2 meters above ground was adjusted for homogeneity and abrupt discontinuities by the National Meteorological Information Centre (NMIC) of the China Meteorological Administration (CMA). Monthly precipitation was the monthly accumulation of daily precipitation and was used to calculate drought index. The stations with missing data for five or more days were excluded. As a result, a total of 2206 stations were retained for the analyses in this study.

The Mainland China was divided into seven regions (Figure 1a) to analyze the spatial variation of heatwave-drought compound extremes, droughts and heatwaves according to regional climate background and socioeconomic situation at the provincial scale: Central China (CC), East China (EC), North China (NC), Northeast China (NEC), Northwest China (NWC), South China (SC) and Southwest China (SWC) (Wu et al., 2019; Ye et al., 2019).

2.2 Evaluation of heatwave events and drought events

Heatwave generally refers to consecutive hot days during which the air temperatures are excessively higher than normal. Many temperature metrics have been used to define heatwave event, including daily maximum surface air temperature (Tmax) (Luo and Lau, 2017; Fischer and Schär 2010), daily mean surface air temperature (Anderson and Bell, 2011) and daily minimum surface air temperature (Tmin) (Liao et al., 2018). Considering the disastrous impacts of extreme temperature and strong land-atmospheric feedbacks (such as evapotranspiration) in daytime, we selected daily Tmax to define heatwaves in this study. Thus, we identified a heatwave as a period comprising at least three consecutive days with daily Tmax exceeding its corresponding historical 90th percentile threshold (Perkins and Alexander, 2012). The 90th percentile threshold was determined by ranking the 15-day temperature samples surrounding a calendar day (i.e., 7 days before and after the calendar day) over 38 years (1980-2017) (Figure 1b). To examine spatiotemporal changes in heatwave-drought compounds and quantified the differences of heatwave intensity and duration between heatwave-drought compounds and heatwaves alone in China, we focused on the heatwave measures including: the yearly number of heatwave events (HWN), length of the longest yearly event (HWD), hottest day of the hottest yearly event (HWA), average length of all yearly events (HWL) and average magnitude of all yearly events (HWM). These indicators have been used to study heatwave characteristics in other studies (Luo and Lau, 2017; Lin et al., 2018; Wu et al., 2021).

Drought is a prolonged absence or marked deficiency of precipitation, and it can be quantified and described in absolute terms (e.g., the amount of soil moisture and lake levels) or relative measures (e.g., SPI, SPEI and PDSI) (Trenberth et al., 2013). The criteria for determining the start and end of a drought or wet spell vary and historical records of direct measurements of the dryness and wetness of the ground (such as soil moisture content) were sparse (Robock et al. 2000; Dai et al., 2004). Thus, we selected the SPI index to identify droughts in our study. SPI is a normalization of precipitation values and can be calculated at different timescales (Mckee et al., 1993), and it has been recommended as the indicator to track the meteorological drought by the WMO (Hayes et al 2011). Rather than SPEI and PDSI, we use SPI calculated with the precipitation only, which isolated the interactive impacts of water availabilities and temperature changes. Here we calculated SPI at a one-month time scale and a meteorological drought event was defined as SPI < -0.5 (Figure 1c) (Wu et al., 2019).

2.3 Evaluation of heatwave-drought compounds

Heatwave-drought compounds are events when a heatwave occurs simultaneously with a drought, while heatwave alone refers to an event when a heatwave occurs without a accompany drought. For each station, we first extracted the start date of a heatwave, and then checked the SPI value in the month of heatwave. If SPI reached the drought level this heatwave was classified as a heatwave-drought compound, otherwise it was classified as heatwave alone (Figure 1d). When there were one or more heatwaves that happened during one drought period in a month, we considered this as one heatwave-drought compound, which ensured that the number of droughts and heatwaves were not fewer than the number of heatwave-drought compounds (Ye et al., 2019). The heatwave duration and heatwave intensity in the heatwave-drought compounds were calculated to compare with that in the heatwaves alone. The heatwave intensity and duration in these heatwave-drought compounds were the mean value of the multiple heatwaves during a monthly drought period.

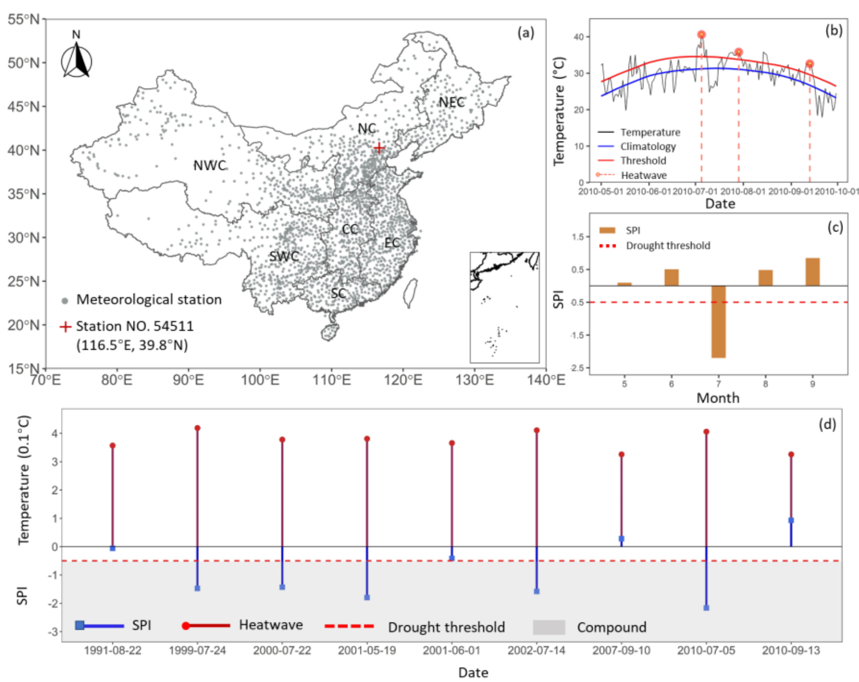

Figure 1 (a) Spatial distribution of meteorological stations and seven subregions in China, (b) an illustration of heatwave extraction in year 2010 at an example station (station NO. 54511 shown in a), (c) an illustration of drought evaluation in year 2010 at an example station (No. 54511),

and (d) an illustration of all the heatwaves and the heatwave-drought compounds at an example station (No. 54511). The "+" in (a) denotes the location of station NO. 54511.

As the stations are not evenly distributed across space, we calculated an area-weighted average for the heatwave characteristics at the regional or national scale (Zhai et al., 2005; Jones et al., 1996). In doing so, we first divided the region into 2° × 2° boxes and then calculated box values as the arithmetic mean of all available station data in the box. Afterward, we used box values to compute the regional or national average by taking the areas of boxes as weights. The linear trends of heatwave characteristics variation over time were assessed using Pearson's Correlation Tests (Pearson, 1895), and the statistical significance of the linear trend was assessed at the 95% level. A Mann–Kendall (MK) test for breakpoint detection in the time series was employed (Mann, 1945; Kendall, 1975). The MK test is a nonparametric method that can reveal the changing trend in a time series, and has been widely applied in climatology. Two standardized statistic series (UF curve and UB curve, representing the statistics of forward and backward sequence, respectively) were calculated. If the UF and the UB curves intersected within the confidence zone, the null hypothesis is rejected and a significant abrupt change is identified. The present study used the confidence level of 95% (1.96 and -1.96) as the boundary lines of the confidence zone. Empirical cumulative density function (ECDF) was used to investigate the difference in the frequency of heatwave-drought compounds before and after the year of significant increase. The two-sample Kolmogorov–Smirnov (KS) test was used to assess the difference in ECDFs. Meanwhile, the climatological mean fraction of heatwave-drought compounds, which was calculated as the ratio of the frequency of heatwave-drought compounds to the frequency of all heatwaves, was designed to analyze the hotspot areas of heatwave-drought compounds in China.

To assess changes in the frequency of heatwave-drought compounds, the data were divided into two periods based on the MK test: 1997-2017 and 1980-1996. Here, the percent change was calculated based on the difference in the number of events in 1997-2017 relative to 1980-1996, divided by the total number of events. This method has also been used in analyses in other regions. For example, Mazdiyasni and AghaKouchak (2015) applied this method to study heatwave-drought compounds variation in the United States, and Sharma and Mujumdar (2017) used this method to examine the changes in the frequency of heatwave-drought compounds in India. To further investigate changes of heatwave-drought compounds, we also calculated the percent changes for droughts and heatwaves. The probability density functions (PDF) of percent changes for heatwave-drought compounds, heatwaves and droughts were analyzed. The nonparametric Wilcoxon rank-sum test (Bethea et al. 1995) was used to test the differences of heatwave intensity and duration between heatwave-drought compounds and heatwaves alone in China.

3 Results

3.1 The increased occurrence of heatwave-drought compounds

The map of climatological mean fraction of heatwave-drought compounds showed that the heatwave-drought compounds frequently occurred in the NC, NEC, SWC, SC and NC, while the fraction was lower in CC and the northern EC (Figure 2a). The occurrence of heatwave-drought compounds and heatwaves alone increased significantly during 1980-2017, while the increasing trend of heatwave-drought compounds was 0.04 events per decade, which was higher than that in heatwaves alone 0.02 events per decade (Figure 2b). MK trend analysis showed that there was an intersection point between UF and UB curves around 1996, and the intersection point was within in the confidence interval (-1.96 < statistical value < 1.96) (Figure 2c). Combined with the time series analysis, we found that there was an abrupt change of the occurrence of heatwave-drought compounds in 1996. The upper tail of ECDF in 1997-2017 curve shifted to the right, which indicated more frequent of compound events in 1997-2017 in relative to the baseline period during 1980-1996 (Figure 2d). The two sample KS test (p < 0.01) successfully detected changes in the distribution of the occurrence of heatwave-drought compounds during 1997-2017 in relative to the base period. The annual mean occurrence of heatwave-drought compounds was about 1.07 events during 1980-1996, but then increased to 1.19 events during 1997–2017, a growth by about 1.11 times more.

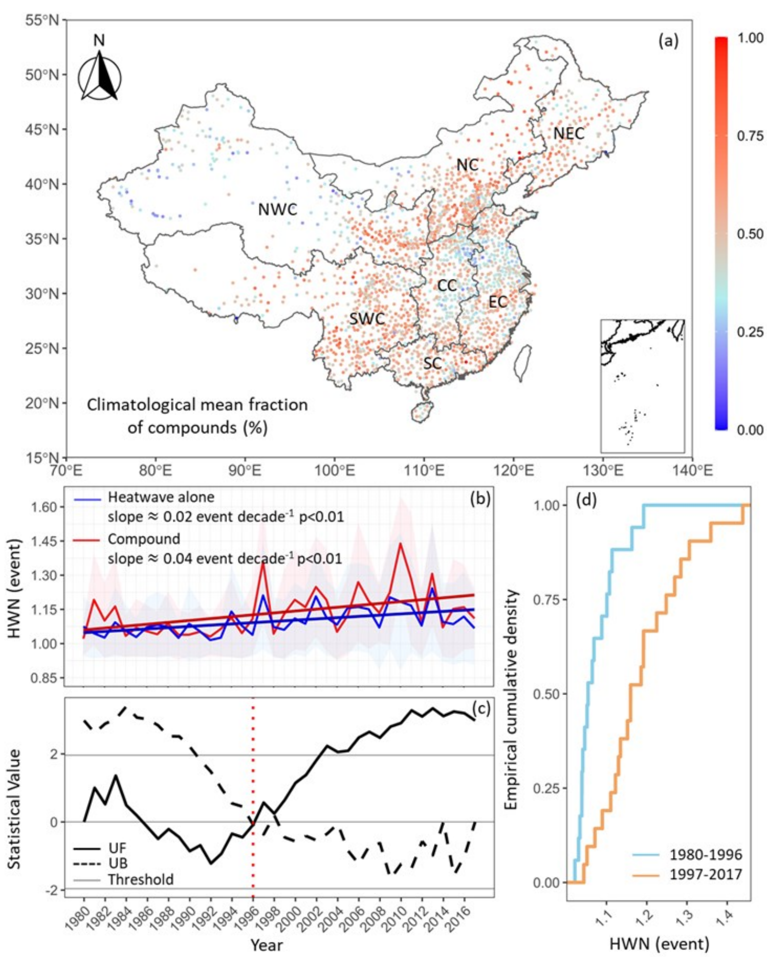

Figure 2 (a) The climatological mean fraction of heatwave-drought compounds in China during 1980-2017, (b) the HWN variation of heatwave-drought compounds and heatwave alone in China during 1980-2017, (c) the MK test for the HWN of heatwave-drought compounds in which an abrupt change point was detected around 1996, and (d) ECDFs for the HWN of heatwave-drought compounds during 1980-1996 and 1997-2017.

To better understand the spatial pattern of changes for heatwave-drought compounds, all heatwaves and droughts regardless of the compound or the alone, percent change of occurrences during 1997-2017 in relative to that in the baseline period 1980-1996 at each station were presented in Figure 3. The occurrence of heatwave-drought compounds increased substantially in most part of China, especially in NC, NWC and SWC, but decreased in some parts of NEC, EC, CC and SC. Meanwhile, the occurrence of heatwaves increased almost at all stations, while the changes of droughts were small. At the national scale, the mean occurrence changes in heatwave-drought compounds, heatwaves and droughts were 44.98%, 9.95% and 48.47%, respectively. Station-based changes revealed that increased heatwave-drought compounds in 99.36% (2011 out of 2024) stations were accompanied with increased heatwaves, while increased heatwave-drought compounds in 79.25% (1604 out of 2024) stations were accompanied with increased droughts (Figure 3e). It implied that heat excess was possibly a larger contributor to the change of heatwave-drought compounds compared with precipitation deficit.

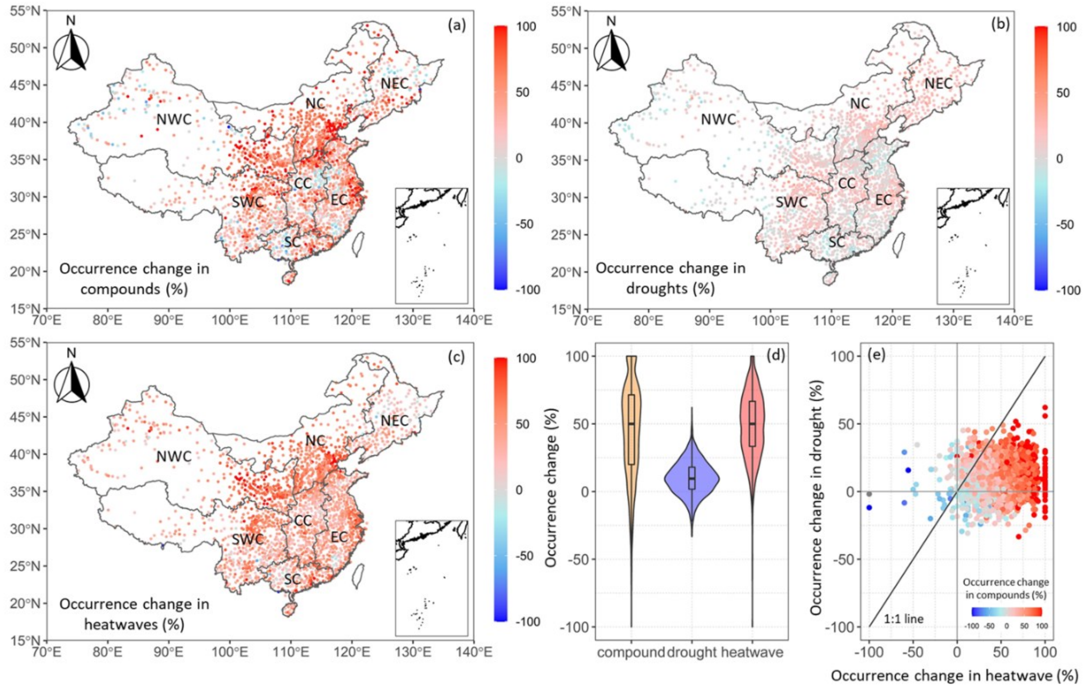

Figure 3 Occurrence change (%) in (a) heatwave-drought compounds, (b) droughts, and (c) heatwaves during 1997-2017 in relative to that during the base period 1980-1996 at the station level; (d) occurrence change (%) of heatwave-drought compounds, droughts and heatwaves at the national level; (e) occurrence change (%) in heatwave-drought compounds associated with occurrence changes (%) of drought and heatwaves.

We examined the probability distribution functions of occurrence change for total number of events during 1997-2017 in relative to the base period 1980-1996 for heatwave-drought compounds, droughts and heatwaves (Figure 4). The distributions of heatwave-drought compounds, heatwaves and droughts were all showed regular unimodal patterns conformed to the Gaussian distribution. The probability distribution function of occurrence change for heatwave-drought compounds can be well fitted in the form of a product of probability distribution function of droughts and heatwaves, indicating that the occurrence change of the heatwave-drought compounds was not a linear addition of droughts and heatwaves. We also found from the distribution pattern that the occurrence changes in heatwaves played a dominant role in the occurrence change in heatwave-drought compounds. Compared to heatwaves, the right tile of the distribution of the heatwave-drought compounds was obviously higher, which indicated the more intensive increase in occurrence of heatwave-drought compounds than the heatwaves.

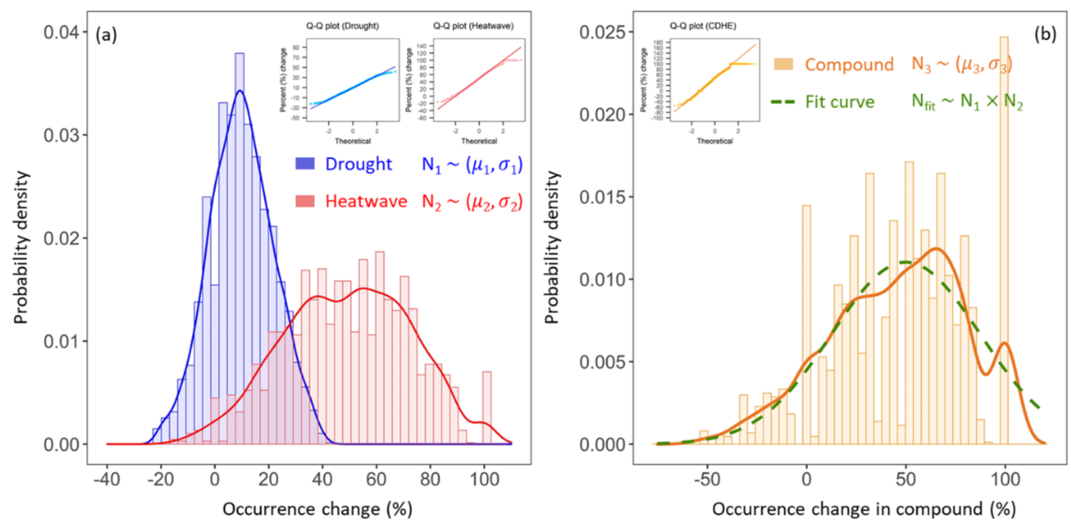

Figure 4 (a) Probability distribution functions of occurrence change (%) for droughts and heatwaves, and corresponding normal probability (or quantile-quantile, Q-Q) plot for droughts and heatwaves, and (b) probability distribution functions of occurrence change for heatwave-drought compounds and nonlinear fitting curve by drought and heatwave probability distribution function.

3.2 The amplified heatwave intensity and duration in the compound extremes

Compared to heatwaves alone, the HWA and HWM were intensified in heatwave-drought compound (Figure 5). The differences of HWA and HWM between heatwave-drought compounds and heatwaves alone in all subregions passed the Wilcoxon rank-sum test at 95% confidence level. The national mean of HWA was 34.24℃±4.39℃ in heatwave-drought compounds, while it was 33.33℃±4.35℃ in heatwaves alone. The national mean HWM in heatwave-drought compounds and heatwaves alone were 32.59℃±4.48℃ and 31.78℃±4.45℃, respectively. Overall, the mean HWA of heatwave-drought compounds was about 0.91℃ higher than that of the heatwaves alone. Meanwhile, the mean HWM of heatwave-drought compounds was about 0.81℃, which is higher than that of the heatwaves alone.

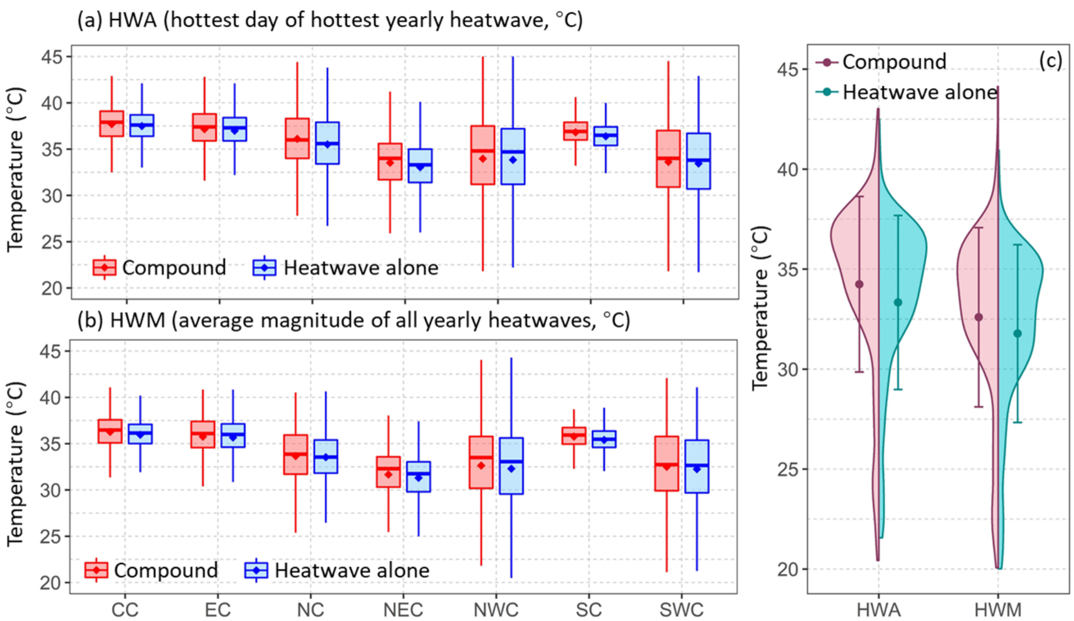

Figure 5 (a) HWA comparison between heatwave-drought compounds and heatwaves alone at the regional level; (b) same as (a) but for HWM; (c) HWA and HWM comparison between heatwave-drought compounds and heatwaves alone at the national level.

For both HWD and HWL, enhanced heatwave durations were observed in heatwave-drought compounds (Figure 6a and d). Compared with heatwaves alone, there were a larger number of heatwaves lasting more than 7 days for both HWD and HWL within the heatwave-drought compounds, especially in SWC, EC and NWC regions (Figure 6b and e). For HWD, the occurrence of long-lasting (duration > 7 days) events accounted for more than a quarter of all the heatwave-drought compounds in all subregions (34.42% - 50.70%), while this percentage was much lower in the heatwaves alone (11.82% -21.55%). For HWL, the occurrence of long-lasting (duration > 7 days) events accounted about 31.02% - 47.13% in heatwave-drought compounds and accounted about 9.69% - 19.42% in heatwaves alone. At the national scale, the mean HWD in heatwave-drought compounds and heatwaves alone were 7.01 days and 6.39 days (Figure 6c). Meanwhile, the mean HWL in heatwave-drought compounds and heatwaves alone were 6.83 days and 6.27 days (Figure 6f). The two sample KS test ($p < 0.01$) successfully detected the differences of HWD and HWL between heatwave-drought compounds and heatwaves alone.

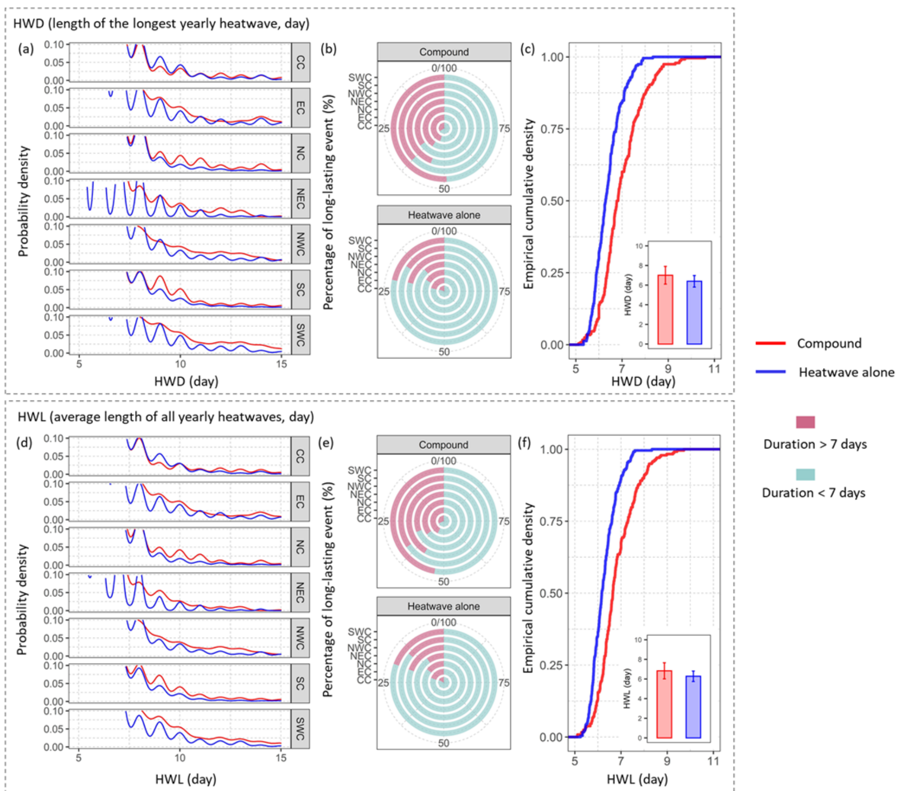

Figure 6 Probability density function of (a) HWD and (d) HWL for heatwave-drought compounds and heatwaves alone in all subregions in China; percentage of long-lasting event (duration > 7days) occurring in heatwave-drought compounds and heatwaves alone based on (b) HWD and (e) HWL; ECDFs and corresponding box-plot of heatwave duration of heatwave-drought compounds and heatwaves alone for (c) HWD, (f) HWL.

4 Discussion

Heatwave-drought compounds occurred frequently in most parts in China, and a significant increase in the occurrence of heatwave-drought compounds during 1980-2017 was observed in our study. These results were consistent with previous studies based on reanalysis datasets (Wu et al., 2019) and interpolated observational datasets (Ye et al., 2019). Synoptic features and circulation patterns have important effects on the occurrence of heatwave-drought compounds. Heatwaves in China were often accompanied by a hot and dry air column (Luo et al., 2020), and the similar persistent large-scale circulation anomalies were also critical for the initiation of both heatwaves and droughts (Quesada et al., 2012; Seager and Hoerling, 2014). It was found that heatwaves in China were accompanied by an anomalous high pressure center and anticyclone near the surface, with anomalous land-sea northwesterly flow, thus reducing sea-land moisture transport and drying the atmosphere over land (Luo and Lao, 2017). Meanwhile, the strengthened anticyclonic circulation and increased geopotential height over the mid- and high- latitudes of Eurasia led to the increasing of frequency and intensity of heatwave-drought compounds in northwest China (Li et al., 2018). The Pacific Decadal Oscillation (PDO) phase transition during the early 1990s may also contribute to the variability of heatwaves in China (You et al., 2016).

The occurrence change analyses of heatwave-drought compounds, heatwaves and droughts implied that heat excess was possible a larger contributor to the change of heatwave-drought compounds compared with precipitation deficit. A century-long ground-based observation revealed that meteorological drought was the main driver of dry-hot events in the 1930s, however, the observed warming has become the dominant driver of dry-hot events in recent decades (Alizadeh et al., 2020). The rising temperatures were also found to be the main driver of increased occurrence of dry-hot events in Europe (Manning et al., 2019). In addition, we found a nonlinear relationship between the occurrence of heatwave-drought compounds and the occurrence of individual droughts or heatwaves. The regions with stronger increases in both droughts and heatwaves showed greater increase in compound extremes. However, in some regions, e.g., the northern EC and eastern SWC, the occurrence of compound extremes was amplified as the increase of individual droughts or heatwaves was not as strong as that of the compound extremes. Improved understanding of the nonlinear relationship between compound extremes and individual extremes has the potential to improve the predictability of extremes under a changing climate and provide basis for mitigating the negative effects of compound extremes because the impacts of compound extremes were greater than that from individual extremes alone (Leonard et al., 2014; Wu et al., 2020).

The intensity and duration of heatwave were enhanced in the heatwave-drought compounds in relative to that in the heatwaves alone. The land-atmosphere coupling acted as a key driver of the increase in severity and frequency of compound events. From the perspective of soil moisture and evaporation, drier conditions favor more sensitive heating and less evaporative cooling, and then a larger fraction of incoming radiation which led to an accumulation of sensible heat in the atmosphere that exaggerated the magnitude of heatwave (Trenberth and Shea, 2005; Zaitchik et al., 2006; Miralles et al., 2019). Meanwhile, higher temperatures lead to larger evaporation rates, potentially resulting in drier conditions (Seneviratne et al., 2010). From the perspective of atmospheric state, studies found that the potential positive feedbacks between droughts and heatwaves contributed to the development of deep and warm boundary layer, which may cause more intense and longer lasting heatwaves (Santanello et al., 2012; Miralles et al., 2014). In addition, the influence of urbanization on heatwaves was reported in recent studies (Liao et al., 2018; Zhao et al., 2018; Jiang et al., 2019). For example, the contribution of urbanization to daytime heatwave duration in China was about 22.47% (Kong et al., 2021), while the contribution of urbanization to the frequency of nighttime heatwave was approximately 50% in Fujian Province, China (Lin et al. 2018). The potential synergistic interactions between urban heat island and heatwave may also have influence on compound extremes. In future studies, more attentions can be paid to the difference of compound heatwave events in urban and rural areas.

5 Conclusions

In this study, we found that there was a significant increase in the occurrence of heatwave-drought compounds during 1980-2017 in China. Spatially, the occurrence frequency of heatwave-drought compounds has increased widespread across China, especially in North, Northwest and Southwest China. The occurrence change of heatwave-drought compounds was not a linear addition of individual droughts and heatwaves in both spatial pattern and statistical distribution. Meanwhile, the heat excess was possible a larger contributor to the change of heatwave-drought compounds compared with precipitation deficit. The heatwave intensity and duration were enhanced in the heatwave-drought compounds compared with the heatwave alone. The national mean HWA in heatwave-drought compounds was 34.24℃±4.39℃, which is higher than that in the heatwaves alone 33.33℃±4.35℃. Meanwhile, the occurrence of long-lasting (duration > 7 days) events accounted for more than a quarter of all the heatwave-drought compounds in all subregions (34.42% - 50.70%), while this percentage was much lower in the heatwaves alone (11.82% -21.55%). Our results highlighted the amplified heatwave severity and duration in the heatwave-drought compounds versus the heatwaves alone.

Acknowledgments

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