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More frequent, long-lasting, extreme and postponed compound drought and hot events in eastern China

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ABSTRACT

As a result of global warming, compound extreme events become more frequent across the world. Compound drought and hot events (CDHEs) are receiving increasing attention because their social and environmental impacts are greater than those of individual extreme events. This study uses the standardized precipitation index (SPI) and maximum temperature, to define CDHEs based on the two-dimensional definition on the daily scale, in eastern China during the warm season (May - October) from 1961 to 2018, identify hot spot areas of CDHEs, and explore the multiple characteristics and variations of CDHEs. The main results are as follows: North China (NC) and Southwest China (SWC) were selected as hot spot areas due to their high-frequency of compound days and the increasing trend in the number of days and land area ratio affected by compound days. CDHEs have become more frequent, long-lasting and extreme in eastern China, especially in NC. Although the change in SWC is not as great as that in NC, the proportion of extreme events in all the severities and the proportion of long duration events in all the durations are larger in SWC than in the other regions. The probability distribution of occurrence date was unimodal in the entire eastern China and it was similar in NC. Whereas, the probability distribution was bimodal in SWC. The occurrence dates of CDHEs with different severities and durations postponed in 1991–2018 compared to 1961–1990, and this feature was the most pronounced in SWC. This study contributes to raising awareness of CDHEs and informs the mitigation of their adverse effects.

1. Introduction

Global climate change accelerates water cycle at global and regional scales (Ma et al., 2018), and alters relevant processes such as precipitation, evapotranspiration, and runoff (Hattermann et al.,2015). Many studies show that extreme weather and climate events are likely to increase in the future (Dosio et al., 2018; Naumann et al., 2018; Jiang and Wang, 2021). Traditionally, the research on extreme weather and climate mainly focuses on single process or variable, such as heavy precipitation or maximum temperature (Rahmstorf and Coumou, 2011; Horton et al., 2016). However, climate variables are interrelated, thus focusing on individual extreme variables may not be sufficient to fully describe the impacts of extreme events. Compound extreme events, that is, the concurrent or continuous occurrence of multiple extreme events, can exacerbate adverse impacts, and result in more severe consequences on human society and natural environment than those individual extreme events do (Leonard et al., 2014).

Drought and hot extreme events are two severe climate hazards in the world, which can lead to major natural disasters with serious social and environmental impacts (Ciais et al., 2005). Drought affects the growth and development of crops and vegetation and causes reduced river flows and lower lake and reservoir levels, leading to problems such as crop shortages and water shortages (Wilhite, 2000; Hao and Aghakouchak, 2013). Hot extreme events have adverse effects on human health, crop and vegetation growth, air quality and so on (Vautard et al., 2005; Lesk et al., 2016). With the changes of global climate, the occurrence of drought and hot events has increased in both global and regional areas (Dai, 2011). Drought and hot events often occur

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simultaneously. Compound drought and hot events (CDHEs) are typical of compound extremes, such as the simultaneous occurrence of drought and heat waves in Europe in 2003, Russia in 2010 and California (USA) in 2014 (Fink et al., 2004; Trenberth and Fasullo, 2012; AghaKouchak et al., 2014), accompanied by high mortality rates and huge economic losses, making them one of the most catastrophic compound events. In many regions of the world, the frequency, number of days and severity of CDHEs have increased (Mukherjee and Mishra, 2020). Hao et al. (2018) assessed changes in the severity of CDHEs on a global scale based on the Standardized Dry Hot Index (SDHI). Their research showed that CDHEs in the western USA, northern South America, Western Europe, Africa, Western Asia, Southeastern Asia, southern India, northeastern China and eastern Australia increased significantly in severity during the warm season. Recent studies indicate that CDHEs occur more frequently from northeast to southwest China (Wu et al., 2019; Kong et al., 2019; Yu and Zhai, 2020).

In China, drought and extreme hot events are extensively studied as individual extreme events. In recent decades, there has been an increasing trend of drought across China, especially over the northern regions, which have become more frequent, more serious and longer-lasting (Yu et al., 2014; Chen and Sun, 2015; Shao et al., 2018). Extreme hot events rose significantly across China over the last few decades, but has dropped slightly in the central regions (Ding et al., 2010; Wei and Chen, 2011). There is an important research gap in the study of concurrent droughts and heatwaves, which have heavier impacts on physical health, social economy and ecological environment. At present, several studies of CDHEs in China have been conducted (Li et al., 2021; Kong et al., 2019) However, most studies of CDHEs are based on relatively coarse resolution at the monthly scale, and focus on the few characteristics such as the frequency and severity of occurrence. Being heavily populated, economically developed, and vulnerable to climate changes, eastern China will suffer from high social and economic losses for compound drought and hot extremes. More detailed information such as severity, duration and starting time is helpful to enhance the understanding of CDHEs and cope with the adverse effects, which is important for disaster prevention and reduction and regional sustainable development.

Frequency, severity, duration and occurrence date are the key attributes of CDHEs. Therefore, it is essential to identify the CDHEs on the daily scale and explore the multifaceted characteristics and changes of CDHEs to mitigate their adverse effects. This study uses the standardized precipitation index (SPI) and maximum temperature, to define CDHEs based on the two-dimensional definition on the daily scale, in eastern China during the warm season (May - October) from 1961 to 2018. First, the general characteristics of compound drought and hot days (CDHDs) were analysed in eastern China. Secondly, the study area was partitioned and the two most severe regions were selected as hot spot areas for further study. Thirdly, the spatio-temporal variation of the CDHEs was investigated for different severities and durations. Lastly, the study focused on the probabilities of occurrence dates of CDHEs to explore their possible temporal migration.

2. Data and methods

2.1. Data

CN05.1 high resolution gridded (0.25°×0.25°) daily precipitation and maximum temperature (T_{max}) datasets (Wu and Gao, 2013) from 1961 to 2018 was used in this study. CN05.1 is a gridded dataset based on the interpolation of daily observation of more than 2400 stations in China obtained from the National Meteorological Information Center. The warm season (May to October) is considered to cover most of the high temperature and low precipitation extreme events in this study.

2.2. Study area

The selected area for this study is eastern China (mainland China within 14.75°N-55.25°N, 97°E-140.25°E), including North China (NC), Northeast China (NEC), East China (EC), South China (SC), Central China (CC), part of Southwest China (SWC) and part of Northwest China (NWC) of China's geographic divisions. The entire region has complex topographic and climatic conditions. Moreover, most of the population in China concentrates in eastern China. There is growing concern about the impacts of extreme weather events on human society and the natural environment, especially in densely populated areas.

2.3. Definitions of CDHDs and CDHEs

Drought is defined according to meteorological drought, which refers to the phenomenon of insufficient precipitation in which the precipitation is lower than the climate average over a period of time. The Standardized Precipitation Index (SPI) (McKee et al., 1993) was used to quantify drought in this study. SPI is a normalization of precipitation, which is usually obtained by summing the precipitation over several months (cumulative period), then fitting the cumulative precipitation to a probability distribution function (parametric statistical distribution) and converting the probabilities to a standard normal distribution. In this study, SPI was calculated at a daily temporal resolution and the cumulative period was 30 days. The drought threshold of this study is set to be relatively high, thus focusing on more severe drought events. Drought day is defined as SPI smaller than −1.3 and is further classified into three categories: moderate drought ($-1.6 \le SPI < -1.3$), severe drought ($-2 \le SPI < -1.6$) and extreme drought ($SPI < -2$). Hot day is defined as the daily T_{max} higher than the 85th percentile of the daily T_{max} during the warm season. It is divided into three categories: moderate ($T_{max85} < T_{max} \le T_{max90}$), severe ($T_{max90} < T_{max} \le T_{max95}$) and extreme ($T_{max} > T_{max95}$). Compound drought and hot events (CDHEs) refer to drought and hot extreme events occurring simultaneously. The day is named compound drought and hot day (CDHD) when $T_{max} > T_{max85}$ and $SPI < -1.3$ in this study. CDHEs normally consist of consecutive or individual CDHDs. The severity of CDHD is divided into three categories according to the two-dimensional definition shown in Fig. 1: extreme ($T_{max} > T_{max95}$ and $SPI < -2$), severe ($T_{max} > T_{max90}$ and $SPI < -1.6$) - ($T_{max} > T_{max90}$ and $SPI < -1.6$) ∩ ($T_{max} > T_{max95}$ and SPI

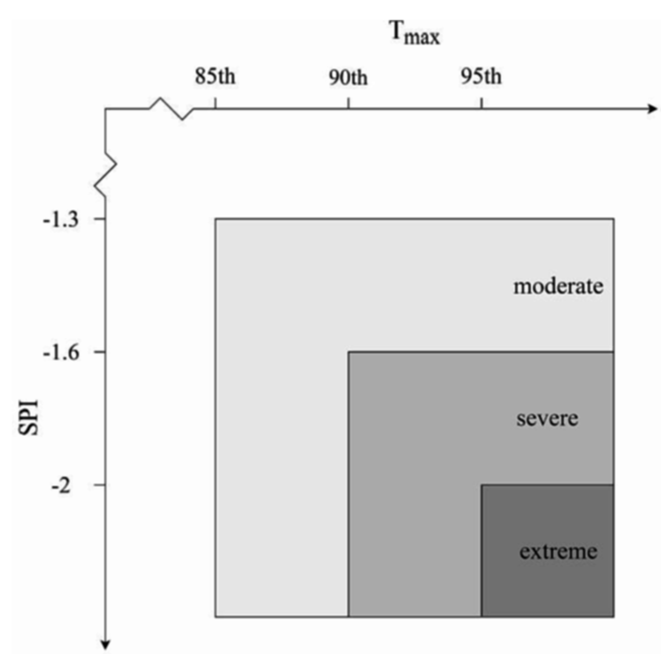

Fig. 1. Two-dimensional definition of CDHD based on SPI and T_{max}.

< -2), moderate ($T_{max} > T_{max85}$ and SPI < -1.3) - ($T_{max} > T_{max85}$ and SPI < -1.3) ∩ ($T_{max} > T_{max90}$ and SPI < -1.6).

In this study, CDHEs are characterized in several aspects, including: (1) CDHEs frequency is defined as the number of annual compound events. (2) CDHEs duration is defined as the number of days that a CDHE lasts. CDHEs are classified into four kinds according to different durations, with 1–2 days being isolated events, 3–5 days being short duration events, 6–10 days being medium duration events and over 10 days being long duration events. (3) CDHEs severity refers to the severity of the day with the highest severity of a compound event lasting for N days. (4) Land area ratio is defined as the ratio of the number of grids affected by CDHEs to the total number of the study area. (5) CDHEs occurrence date is the date on which a CDHE begins.

Different from previous studies (Hao et al., 2018; Hao et al., 2020), this study provides a new two-dimensional definition of daily scale CDHEs. Meanwhile, the severity of CDHEs is determined by the severity of drought events and high temperature events at the same time, avoiding the case when a combination of a less severe high temperature (drought) and a more severe drought (high temperature) is identified as a more severe compound event.

2.4. Trend analysis

Long term trends are estimated by the slope of the linear regression model. Mann-Kendall (MK) trend test (Kendall, 1948; Mann, 1945) is applied to test the significance of the trend, which is a non-parametric approach and one of the most frequently applied methods for detecting changes in hydrology and climatology.

2.5. Normalized anomaly

Normalized anomalies (x_i') of the frequency of CDHEs for different durations are calculated and derived as:

$$x_i' = (x_i - \overline{x})/\sigma_i \quad (1)$$

where x_i, $\overline{x}$, and σ_i are the frequency, frequency mean and frequency standard deviation of CDHEs for a particular duration respectively. If the normalized anomaly is positive (negative), it indicates that the frequency is greater (smaller) than normal.

2.6. Two-sample Kolmogorov-Smirnov (KS) test

The two-sample Kolmogorov-Smirnov (KS) test is used to assess whether two samples come from the same or different distribution families. KS is a nonparametric test that can evaluate two distribution functions (samples) based on the distance between their empirical distribution functions. The null hypothesis is that the two distribution functions are drawn from the same distribution at a certain significance level (here, at 95 % confidence level). Here, the two-sample KS test is employed to assess differences in the probability distributions of occurrence date in the two time periods. The test indicates whether the data from the two periods come from the same distribution at 95 % confidence level.

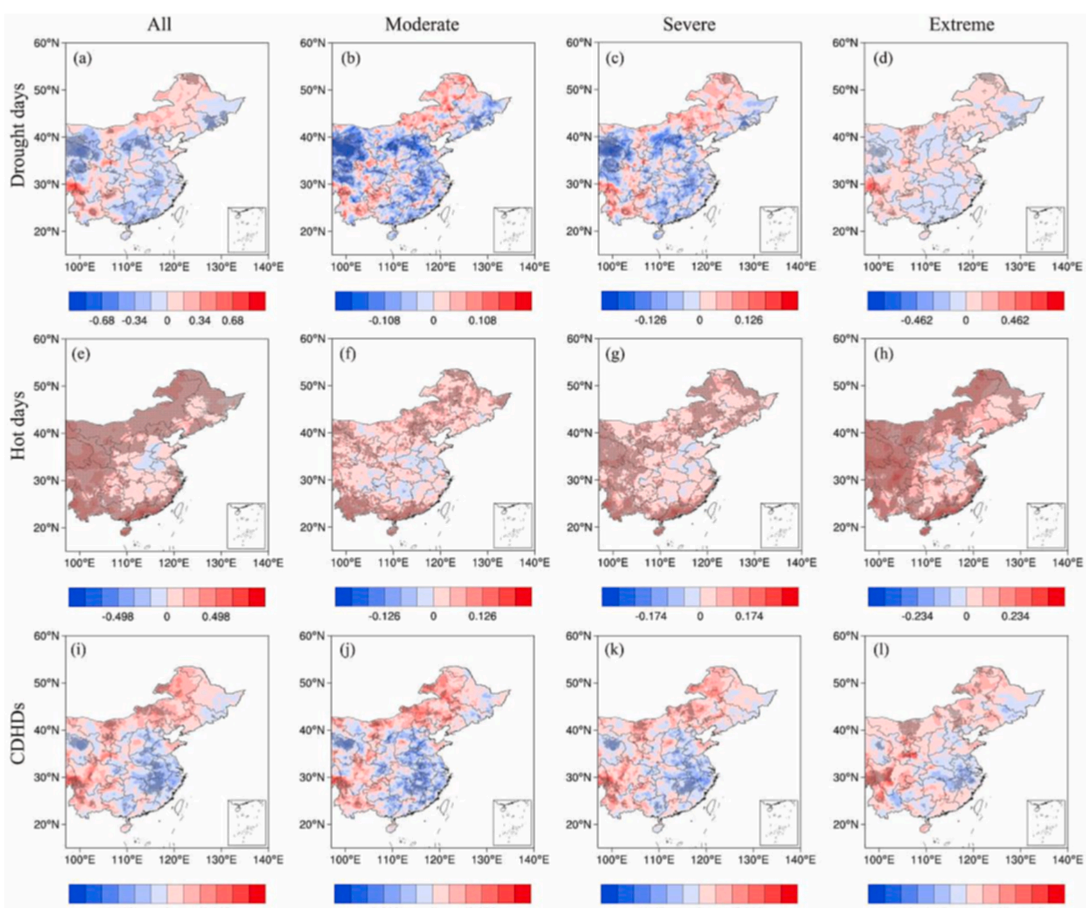

Fig. 2. Spatial distribution of trend in the number of drought days, hot days and CDHDs for the warm season from 1961 to 2018. (Units: days / year, gray shaded areas indicate grids with statistical significance at 95% confidence level).

3. Results

3.1. Variation in drought days, hot days and CDHDs

Based on daily SPI and T_{max}, the changes in the number of drought days, hot days and CDHDs are first analyzed. As shown in Fig. 2, the trends displayed spatial inhomogeneity. From 1961 to 2018, the spatial distribution of the trends in the number of drought days of different severities was generally consistent across the study area (Fig. 2a-d). There was an upward trend in most areas from the north to the southwest of the study area and a downward trend in most of the other regions, with some areas (gray shaded area) showing a statistically significant trend (95 % confidence). This change pattern of drought days is consistent with that of precipitation reduction indicated by Su et al. (2020). Moreover, the upward trend of drought days in the southwestern region increased with the severity of drought, indicating an increasing risk of drought (Xu, 2020). For the number of hot days, most areas showed a significant upward trend at 95 % confidence level, and only some parts of central and eastern region showed a downward trend (Fig. 2e-h). As the severity of high temperature increased, the increasing trends in most regions were greater and the area with a decreasing trend was smaller. The change pattern of hot days is generally consistent with the daytime heat wave change results of Chen and Li (2017). For the number of CDHDs, the spatial distribution of the trends was similar to that of the number of drought days (Fig. 2i-l), which is consistent with the results of previous studies (Yu and Zhai, 2020). The upward trend in the number of CDHDs in northern region decreased as the severity of CDHD increased. The trend of CDHDs in southern region changed from upward trend to downward trend with the increase of severity. In addition, Fig. 3 exhibited the multi-year average of the number of CDHDs. Overall, the number of CDHDs was the highest in southwestern region, followed by northern region, showing that CDHDs occur frequently in these two regions. For moderate CDHDs, those in southwestern and northern region were about the same. However, as the severity increased, the number of days became much greater in southwestern region than that in northern region.

As a result of the vast area of the entire eastern China and the complex and varied topography and climate, the study area was divided into seven sub-regions based on geography and climate: NC, NEC, EC, SC, CC, SWC and NWC (Fig. 4). We further evaluate the number of CDHDs and the land area ratio affected by CDHDs (the sum of the unclassified three categories) in sub-regions. Fig. 4a shows the time series of regional average CDHDs. The number of days had shown an upward trend in the entire eastern China. Significant increase in the CDHDs of NC and SWC were observed, with a significant trend of 0.0559 days/year at 99 % confidence level and a significant trend of 0.0484 days/year at 90 % confidence level respectively. There was no significant change in most of the other regions. Fig. 4b shows the land area ratio affected by CDHDs in each region. The area ratio didn't show a significant trend in the entire eastern China. NC and SWC showed an increasing trend, and the trend in NC (0.0023 %/year) was significant at at 90 % confidence level. Whereas, CC and EC showed a significant decreasing trend, reaching 95 % and 99 % confidence levels respectively.

NC and SWC were high-frequency regions of CDHDs, and the number of CDHDs and land area ratio affected by CDHDs were increasing, which may have greater adverse effects. Therefore, we chose these two regions as hot spot areas for more detailed analysis. Next, we explore the relationship between compound days and drought and high temperature through the time evolution of drought days, hot days and CDHDs. Fig. 5 shows the distribution of occurrence of CDHDs associated with the occurrence of drought and hot days from 1961 to 2018. The change in the number of CDHDs was consistent with the change in the number of drought and hot days, and all of them increased with time (Fig. 5a-c). In order to quantitatively investigate the relationship between compound events and individual events, the correlation coefficient between CDHDs and drought days / hot days is given in Table 1. CDHDs were strongly correlated with drought days / hot days ($\alpha = 0.01$). Thus, the change of compound events was generally closely related to individual changes in the droughts and heat waves. Regional variations in precipitation and temperature can have an impact on CDHEs. The correlation between CDHDs and drought days was generally the same as the correlation between CDHDs and hot days in NC, while the correlation between CDHDs and drought days was greater than the correlation between CDHDs and hot days in SWC. The decrease in precipitation may be the main reason for the increase in compound drought and hot events in SWC. The evolution of the number of CDHDs with different severities were further revealed (Fig. 5d-f). In eastern China, the proportion of compound days with extreme severity tended to increase, in line with the evolution of the total number of unclassified three types of CDHDs. The proportion of severe CDHDs also tended to increase, while the proportion of moderate CDHDs showed a decreasing trend. Besides, the trends of extreme CDHDs and moderate CDHDs were significant at 95 % confidence level (Table 2). The proportion of CDHDs in different severities in NC and SWC was consistent with that in eastern China. It indicated that CDHDs would become more extreme, potentially causing more significant risks.

3.2. Variation in the frequency, duration and severity of CDHEs

The above section focuses on the analysis of the number of CDHDs on a daily scale, and next we explore the variation characteristics of non-consecutive and consecutive CDHEs. Fig. 6 displays the spatial distribution of trend and the multi-year average of frequency of CDHEs in warm season from 1961 to 2018. The trend distribution of the frequency of CDHEs was very similar to that of the number of CDHDs, showing an increasing trend in most areas of northern and southwestern regions and a decreasing trend in the northwestern and southeastern regions. For the multi-year average of the frequency of CDHEs, the frequency in most areas of the southwest and north was higher than that in the other areas. The characteristics of higher frequency in southwestern regions than in other regions become more evident with the severity. Subsequently, Fig. 7 exhibits the spatial distribution of trend and the multi-year average of duration of CDHEs in warm season from 1961 to 2018. The

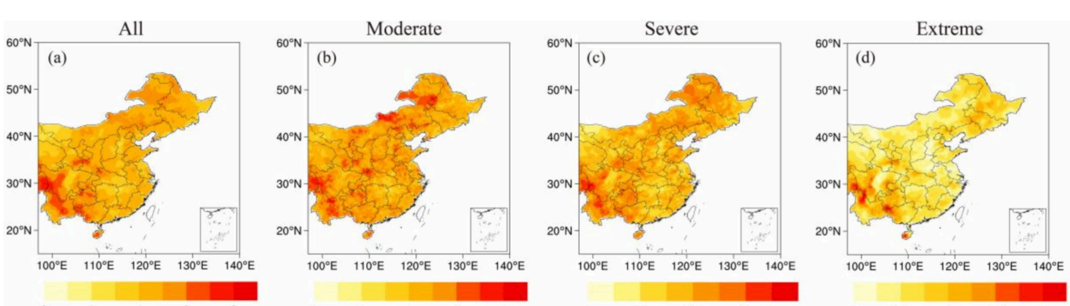

Fig. 3. The average of CDHDs in warm season from 1961 to 2018 (Units: days).

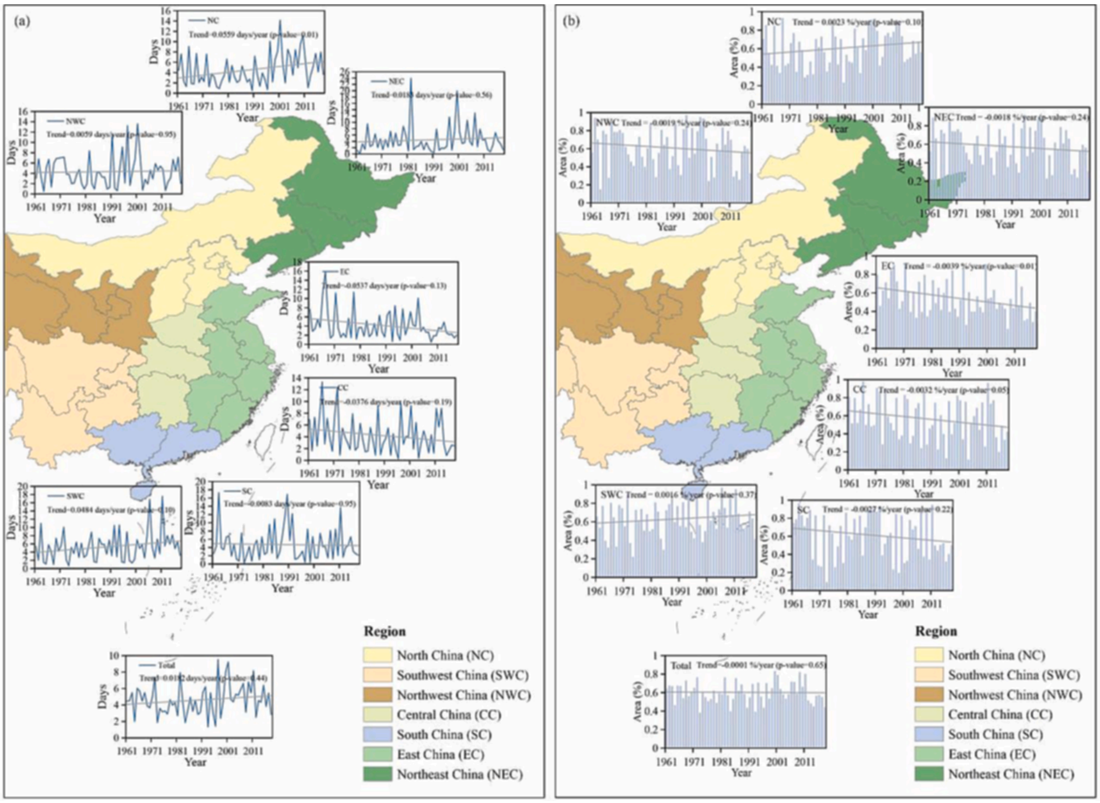

Fig. 4. (a) Time series of regional averages of the number of CDHDs (the sum of the unclassified three categories), (b) land area ratio affected by CDHDs (the sum of the unclassified three categories). Mann-Kendall trend test results in terms of p-values are also shown here.

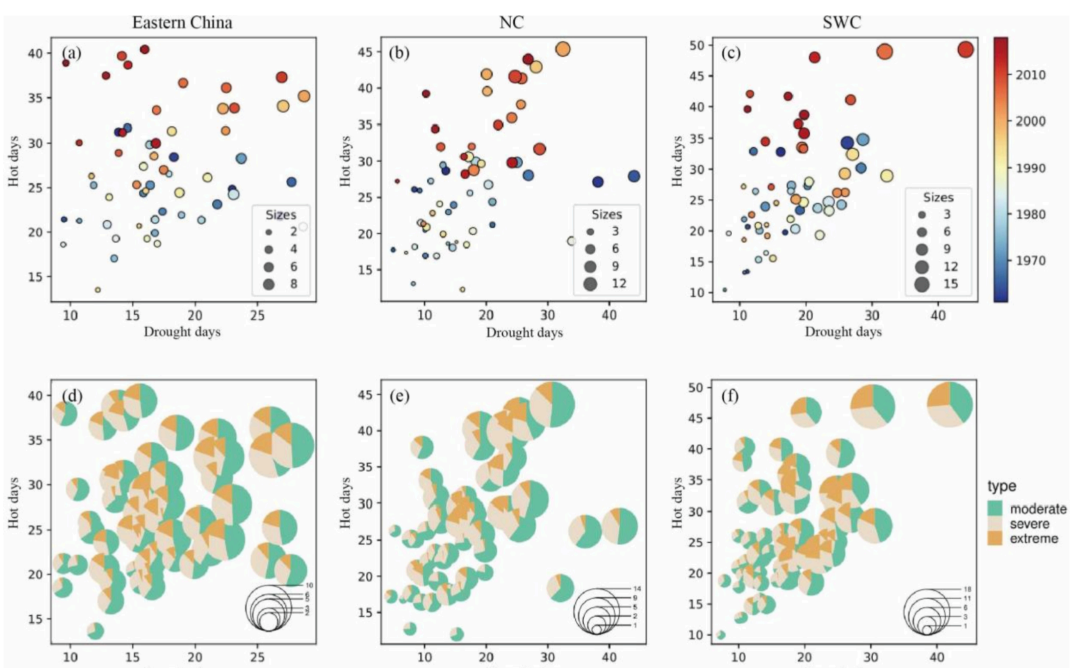

Fig. 5. Relationship of drought days (SPI < -1.3), hot days ($T_{max} > T_{max85}$) and CDHDs in warm season from 1961 to 2018. ((a), (b), and (c) show the total number of CDHDs for the three categories without classification, (d), (e), and (f) show the number of CDHDs with different severities. The horizontal axis represents the number of drought days and the vertical axis represents the number of hot days. The size of the dots in (a) (b) and (c) represents the number of CDHDs and the colour bar indicates the time. The size of the pie in (d) (e) and (f) represents the number of CDHDs and the colour bar represents the different severities of CDHDs.).

Table 1
The correlation between CDHDs and drought days / hot days during the period from 1961 to 2018.

	Eastern China	NC	SWC
	CDHDs	CDHDs	CDHDs
Drought days	**0.77**	**0.78**	**0.89**
Hot days	**0.52**	**0.76**	**0.68**

Values that exceed the 99% confidence level are set in boldface.

Table 2
Trends in the proportion of CDHDs with different severities.

	Eastern China	NC	SWC
Moderate	**−0.14 % (0.007)**	**−0.23 % (0.002)**	**−0.19 % (0.035)**
Severe	0.01 % (0.511)	0.07 % (0.091)	0.04 % (0.265)
Extreme	**0.13 % (0.003)**	**0.16 % (0.002)**	**0.14 % (0.044)**

The p-values of Mann-Kendall trend test are given in parentheses. Values that exceed the 95% confidence level are set in boldface.

trend distribution of duration was similar to that of frequency. Multi-year averages of duration were generally longer in the south than in the north. The distribution of multi-year averages of duration was similar to that of frequency for different severities as well. There was a trend towards increasing frequency and duration in most of the northern and southwestern regions, and their multi-year averages were also higher relative to the other regions. The increasing frequency, persistence and severity of compound events in both regions (NC and SWC) confirms the necessity to select them for more in-depth analysis.

To further explore the change of CDHEs with different durations, the time evolution and trend of normalized anomalies of CDHEs frequency with different durations are provided in Fig. 8. Overall, the frequency was mostly below normal until the 1990 s and then increased to above normal after the early 1990 s. The frequency of CDHEs with all durations had changed since the early 1990 s. In addition, we obtained similar results by using Mann-Kendall test to detect the break point (figure omitted). Most of the significant break points (at 95 % confidence level) were around the early 1990 s. From 1961 to 2018, the normalized anomalies of each duration showed an increasing trend. In eastern China and NC, the trend of normalized anomalies generally increased monotonously with the increment of duration. Whereas, the trend was more evident for shorter and longer durations and less evident for medium durations in SWC. For moderate, severe and extreme CDHEs (Fig. A.1 - Fig. A.3), their temporal changes were similar to those of the unclassified total CDHEs. However, as the severity increases, the characteristics of the events became more pronounced whose frequency tended to be below normal until the early 1990 s and above normal thereafter. In eastern China, trends in the frequency of compound events of all durations were insignificant for both moderate and severe severity, with decreasing trends for shorter events and increasing trends for longer ones. The trend for the frequency of extreme CDHEs of all durations was increasing, with some cases being significant. In NC, the frequency of compound events of all durations of different severities tended to increase. As severity increases, the frequency of CDHEs of different durations increased significantly. In SWC, trend in the frequency of moderate CDHEs of all durations was either increasing or decreasing, but none of them was significant. The trend was increasing for both severe and extreme events, with the frequency of more events showing a significant increase with increasing severity. In a word, the frequency of CDHEs of all durations and severities generally tended to increase, with the characteristics of being mostly below normal until the early 1990 s and mostly above normal thereafter.

Due to the fact that the frequency of CDHEs is negative before the early 1990 s, and positive after the early 1990 s, we further analyze the change of various characteristics in the two periods of 1961–1990 and 1991–2018 to evaluate the changes in compound events. Since CDHEs of different severities and durations all show an increasing trend, we cannot directly compare the changes of events with different severities (durations). Hence, we next analyze the contribution of CDHEs with different severities (durations) to the total CDHEs. Fig. 9 exhibits the percentage of CDHEs with different severities to the total CDHEs. In eastern China, NC and SWC, the moderate events accounted for the largest proportion of all CDHEs in the two periods, followed by the severe events, and the extreme events accounted for the minimum proportion. With the increase of duration, the proportion of moderate events decreased, the proportion of severe events first increased and then decreased, and the proportion of extreme events increased. For the extreme CDHEs with the highest severity, the proportion of extreme CDHEs of each duration was greater in SWC than in eastern China and NC, suggesting that SWC is more prone to extreme CDHEs and its

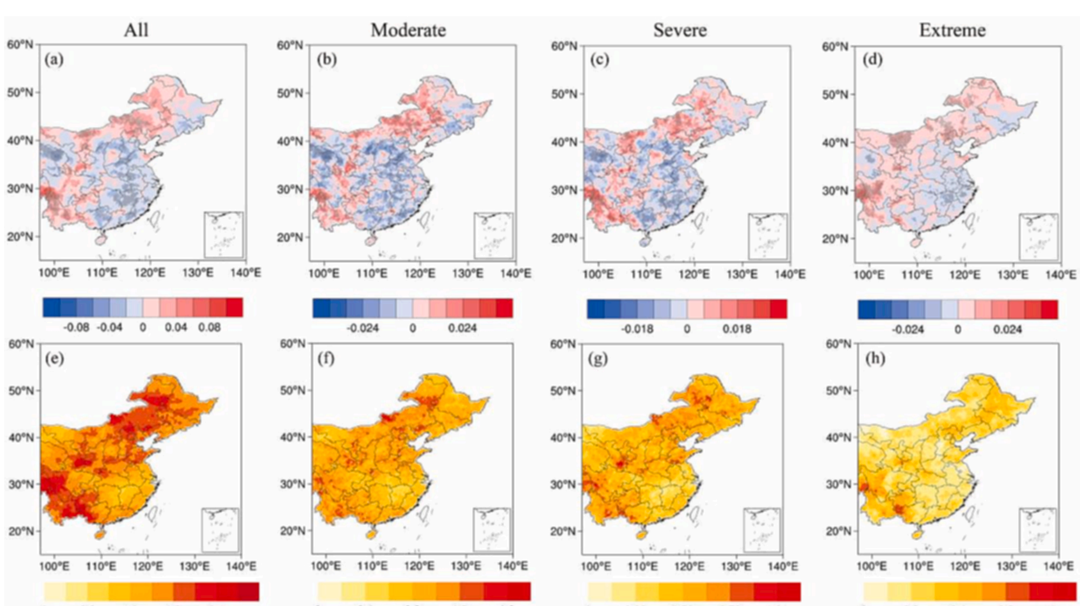

Fig. 6. Spatial distribution of trend (Units: times / year, gray shaded areas indicate grids with statistical significance at 95% confidence level) and multi-year average (Units: times) of CDHEs frequency in warm season from 1961 to 2018.

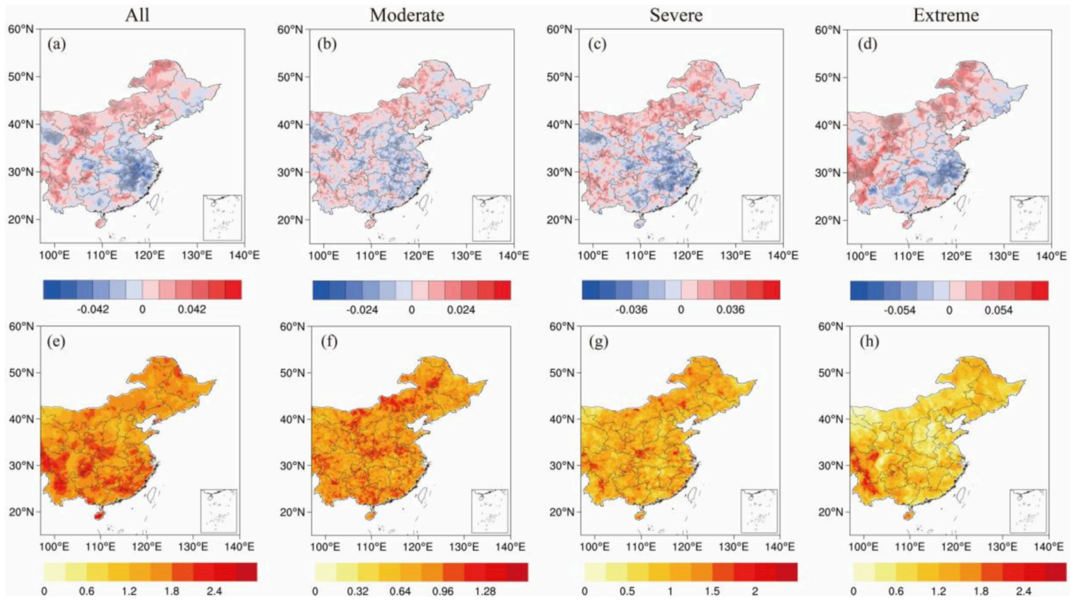

Fig. 7. Spatial distribution of trend (Units: days / year, gray shaded areas indicate grids with statistical significance at 95% confidence level) and multi-year average (Units: days) of CDHEs duration in warm season from 1961 to 2018.

disaster risk was greater. The proportion of extreme CDHEs in 1991–2018 was always larger than that in 1961–1990. A larger proportion of CDHEs with extreme severity indicated that CDHEs become more extreme.

Furthermore, Fig. 10 demonstrates the proportion of CDHEs with different durations to the total CDHEs in eastern China. The stacked histogram is the ratio of the multi-year average occurrence frequency of the two periods to the sum of the two periods. In the two periods, all CDHEs ranked in descending order of duration length as isolated events, short duration events, medium duration events and long duration events. As the severity increases, the proportion of consecutive CDHEs increased for all three categories in both time periods, and the increase was greater for CDHEs of longer duration. The proportion of isolated CDHEs decreases as the severity increases. The same characteristics were observed in NC (Fig. A.4) and SWC (Fig. A.5). In eastern China and NC, the proportion of long duration events and medium duration events with different severities in 1991 to 2018 was always greater than that in 1961 to 1990. The proportion of isolated events in 1991–2018 was always less than that in 1961–1990. The increase in the proportion of CDHEs with longer duration indicates that CDHEs become more lasting. There is no obvious difference in the proportion of events with different durations between the two time periods in SWC. The multi-year average frequency was greater in 1991–2018 than that in 1961–1990. In eastern China and NC, with the increase of duration, the multi-year average frequency from 1991 to 2018 accounted for a greater percentage of the sum of the two periods in most cases, confirming the development of CDHEs toward longer duration. Differences between different durations of the same severity were more pronounced in NC, while there were no apparent differences in the multi-year average frequency of different durations in SWC. The above suggests that the more persistent characteristics of the CDHEs are obvious in NC, while there is no such obvious characteristics in SWC.

3.3. Variation in the occurrence date of CDHEs events

In this section, we investigate the changes in the occurrence date of CDHEs. Fig. 11 showed the trend in the five-year running mean of occurrence probabilities in each date. The trends with different severities were generally consistent. In the entire eastern China, NC and SWC, most of the dates indicated a decreasing trend in the occurrence probability during the months from May to July and an increasing trend in August and thereafter. This change means that CDHEs were postponed in the warm season.

The probability distribution results of CDHEs occurrence date in 1961–1990 and 1991–2018 were used to further analyze the characteristics and changes of occurrence date more visually. Fig. 12 illustrates the probability distribution of CDHEs occurrence date, with the orange and blue bars showing the probabilities in 1961–1990 and 1991–2018, respectively. We used two-sample KS test to assess the differences in the probability distributions of occurrence date of the two time periods. The test results showed that the data for the two periods came from the same distribution at 95 % confidence level. However, we can still observe some changes to get some useful information, although they are not significant. The shape of the probability distribution was similar for different severities. The possible occurrence dates of CDHEs in the three regions during the warm season were from early May to early October (eastern China), early May to late September (NC), and early May to mid-October (SWC), respectively. The possible time range of CDHEs in SWC was the longest. The probability distributions of occurrence date in eastern China and NC were similar in shape, with a single peak. From 1961 to 1990, the probability of occurrence in July (middle June to early July) was the highest in eastern China (in NC), while the date with the highest probability of occurrence from 1991 to 2018 postponed to late July to middle August (NC was the same, but the peaks of extreme severity in both regions had not moved). The probability distribution in SWC is bimodal. From 1961 to 1990, there were two obvious peaks in the probability distribution, with a greater probability of occurrence from middle May to early June and from middle July to early August; whereas from 1991 to 2018, the double peaks in the probability distribution became less obvious, with the former peak weakening and the latter peak strengthening. Moreover, most of the probabilities before late July (middle July) were greater in eastern China and NC (in SWC) during 1961–1990 than during 1991–2018, while the differences between the two time periods was reversed for most of the probabilities after late July (middle July). In eastern China, the differences in cumulative probability before and after late July were about 0.06 between 1961 and 1990 and 1991–2018, with few differences in different severities. The differences were within 0.11–0.21 in NC, and the differences decreased with the increase of severity. However, the differences in SWC increased with severity, and the differences in cumulative

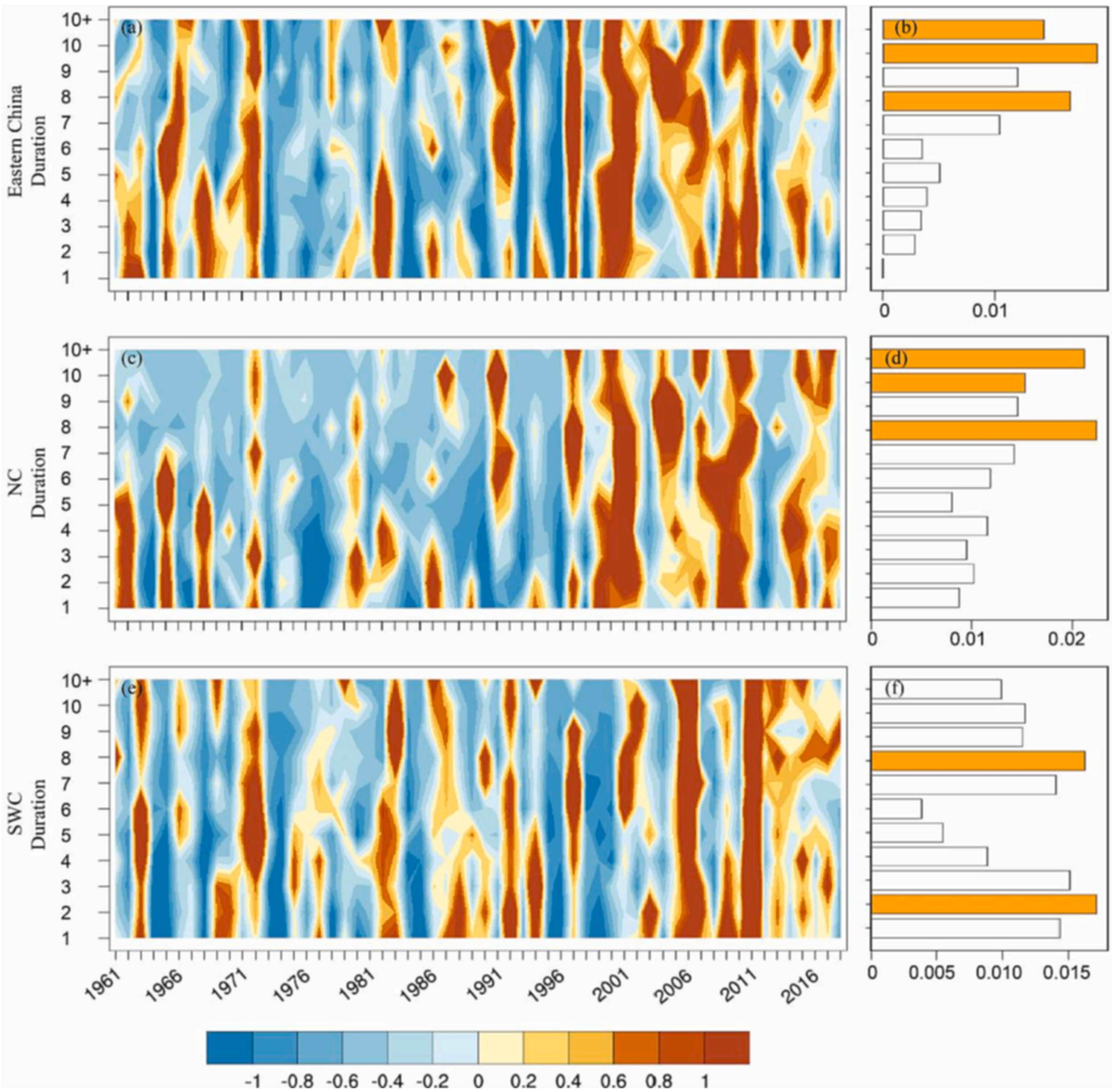

Fig. 8. Temporal evolution (a, c, e) and trends (b, d, f) of normalized anomalies of CDHEs frequency with different durations in warm season (histogram values are trends, coloured bars indicate the statistical significance of the trends at 95% confidence level).

probability before and after middle July were 0.06–0.24 between 1961 and 1990 and 1991–2018. The above results demonstrated that most of the occurrence dates postponed in 1991–2018 relative to 1961–1990, and this change was most pronounced in SWC.

We further investigate the probability of CDHEs with different durations. As the duration increases, the kurtosis of most probability distributions increases (Table 3), and the shape of distribution changes from short and fat to tall and thin, becoming more concentrated. For instance, in eastern China (Fig. A.6), the dates on which CDHEs were concentrated (occurring with approximately 70 % of the total probability) are: early June - late August (1–2 days), mid-June - mid-August (3–5 days), late June - mid-August (6–10 days), and late June - early August (10 + days). The probability distributions with different durations in NC were very similar to those in the entire eastern China (Fig. A.7). In SWC (Fig. A.8), the bimodal character of the probability distribution became increasingly evident as the duration increases.

4. Discussion

The changing characteristics of CDHEs are closely related to the changes in individual events of drought and high temperature. CDHDs occurred frequently throughout eastern China from the 1960 s to the early 1970 s and after the 1990 s (Fig. 4a, Fig. 5a-c). It seems to be related to the fact that several regions of China experienced severe summer droughts in the 1960 s and 1970 s (Yao et al., 2017). The increase in drought and hot events after the 1990 s may have led to an increase in compound events (Yu and Zhai, 2020, Ding and Qian, 2011). Meanwhile, droughts and heat waves have become more frequent in southwestern and northern China (Gong et al., 2017; Jia and Hu, 2017), which is generally consistent with the increase in compound events in these regions. Moreover, more hot events are predicted to occur in the context of a warming climate in the future, resulting in relatively higher mortality (Wang et al., 2017; Wang et al., 2019). With the further intensification of temperature rise in the future, the frequency and risk of compound extreme events will increase (IPCC, 2021). The increase in

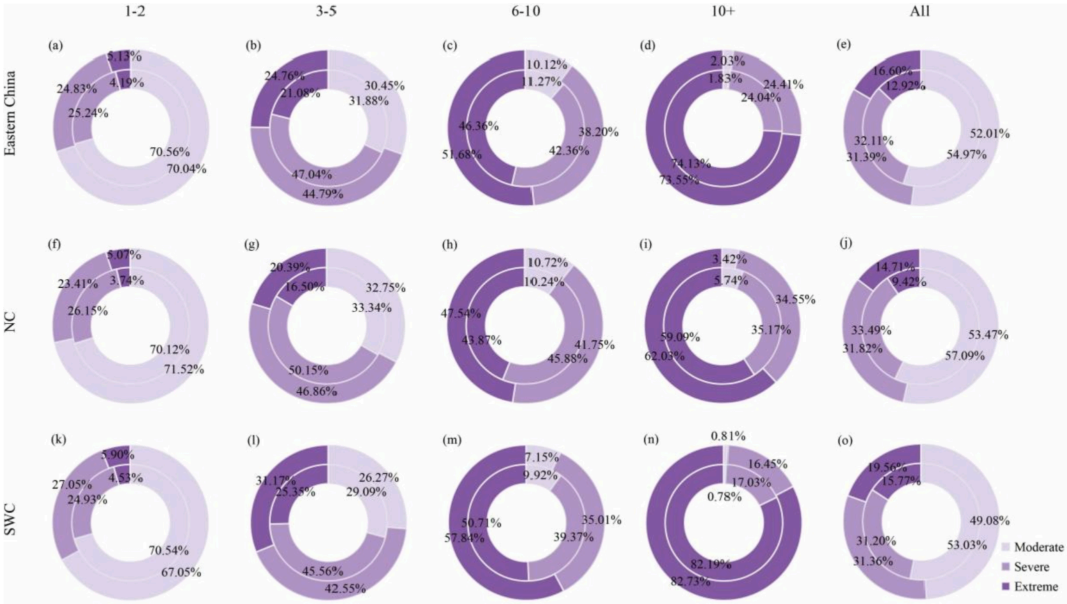

Fig. 9. Percentage of different severities CDHEs to the total CDHEs in eastern China (a-e), NC (f-j) and SWC (k-o). The five columns of pie charts represent isolated events of 1–2 days, short duration events of 3–5 days, medium duration events of 6–10 days, long duration events of 10 + days, and all duration events. (The inner circle of the pie chart represents the period of 1961–1990 and the outer circle represents the period of 1991–2018.).

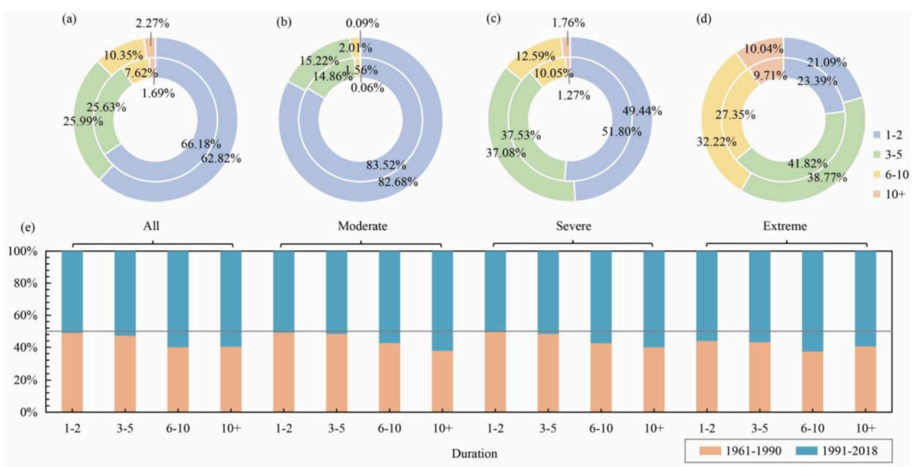

Fig. 10. The percentage of CDHEs with different durations to the total CDHEs in eastern China for (a) all severity, (b) moderate, (c) severe and (d) extreme CDHEs,. (The inner circle of the pie chart represents the period of 1961–1990 and the outer circle represents the period of 1991–2018) (e)The ratio of the multi-year average frequency of CDHEs over the two time periods to the sum of the two time periods.

multiple features of CDHEs strengthens local disaster risk and may pose a greater threat than a single extreme event (Sedlmeier et al, 2018; Schumacher et al., 2019). CDHEs have caused serious social and economic losses in China (Zhang et al., 2022; Feng et al., 2020). Therefore, improving the understanding of CDHEs and providing early warnings is an urgent issue to be addressed.

Furthermore, we found that the probability distribution of the occurrence dates of CDHEs in different regions is quite different. In this study, the distribution is unimodal in NC, while it is bimodal in SWC. This may be due to the fact that the rainy season in SWC has not yet started in May (Yan et al., 2013) when the probability of drought is higher, and the probability of high temperatures is also higher, resulting in a peak in May. The unimodal distribution in NC is because the probability of high temperature is quite small in May, although the probability of drought is high at this time. Meanwhile, most of the occurrence dates postponed in 1991–2018 relative to 1961–1990. This may be related to the delay of rainy season, which is affected by monsoon activity, South Asia high, water vapor transport and the like (Hao et al., 2021; Yan et al., 2013).

However, there are still some points need to be improved in this study. (1) The definition of compound events in this study only considers the daily precipitation and daily maximum temperature. However, meteorological variables such as evapotranspiration, wind speed, relative humidity and radiation also have impacts on compound events (Russo et al., 2019), and some studies have added evapotranspiration to define CDHEs (Jena et al., 2020, Kong et al., 2019). Moreover, extreme high temperatures include not only daytime temperatures but also nighttime temperatures (Wang et al., 2020). (2) In addition to the characteristics and changes of CDHEs, future research should concentrate on the physical mechanism of CDHEs. The changes of compound events are affected by the changes of precipitation and temperature and their dependence (Kong et al., 2019). For instance, sea surface temperature (SST) plays an important role in the variations and trends of extreme temperature and precipitation (Dittus et al., 2018). What is

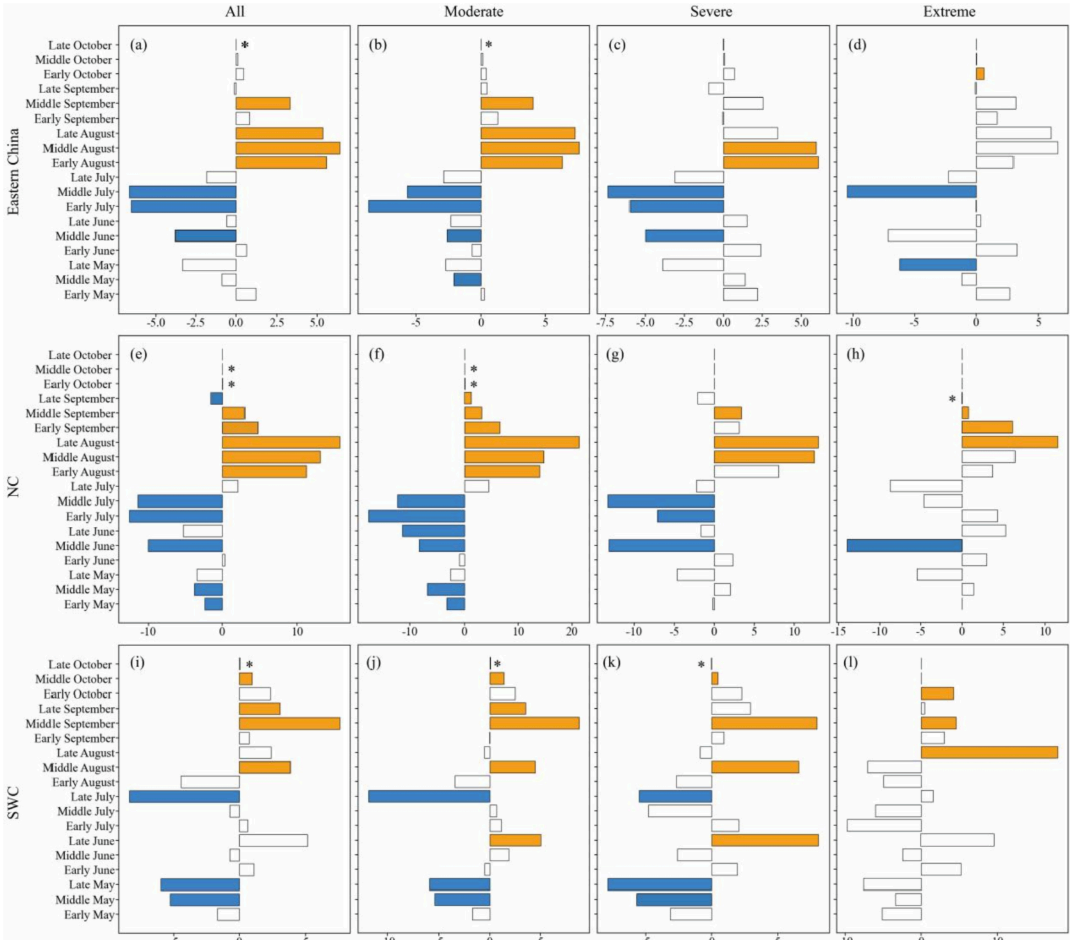

Fig. 11. Trend in five-year running mean of occurrence probabilities of CDHEs in each ten days from May to October (histogram values are trends (value * 10,000 / year), coloured and asterisked bars indicate the statistical significance of the trends at 95% confidence level).

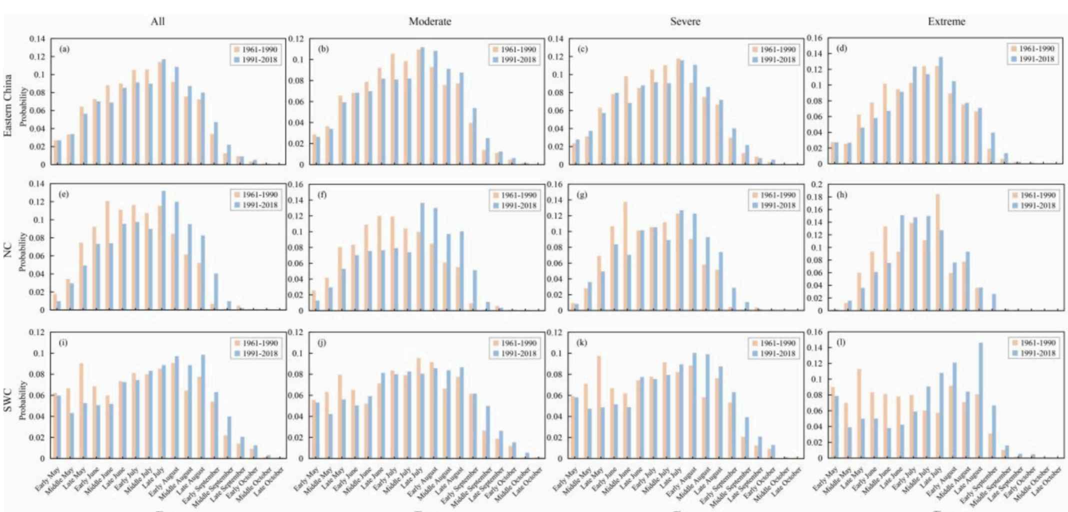

Fig. 12. Probability distribution of CDHEs occurrence date.

more, sustained large-scale circulation anomalies can trigger the occurrence of CDHEs, and land–atmosphere feedbacks can exacerbate and propagate these events (Miralles et al., 2019). Besides, global warming can lead to the enhancement of regional soil moisture-temperature coupling in some water-limited areas, thus amplifying the intensity of heat waves during droughts (Cheng et al., 2019). Therefore, CDHEs are fundamentally influenced by SST anomalies, atmospheric circulations, land–atmosphere interactions and climate warming, and the physical mechanism of CDHEs will be explored in the future.

Table 3
The kurtosis of probability distributions of CDHEs occurrence date for different durations.

Severity	Duration	Eastern China		NC		SWC	
		1961–1990	1991–2018	1961–1990	1991–2018	1961–1990	1991–2018
ALL	1–2	−1.49	−1.25	−1.62	−1.20	−0.89	−0.63
	3–5	−1.33	−1.34	−1.27	−1.51	−1.12	−0.97
	6–10	−1.12	−0.99	−0.31	−0.84	−1.30	2.06
	10+	−1.00	−0.58	0.18	0.23	1.53	2.42
Moderate	1–2	−1.46	−1.29	−1.55	−1.12	−0.85	−0.66
	3–5	−1.21	−1.06	−0.88	−0.86	−1.17	−0.92
	6–10	−0.21	−0.05	0.55	1.94	−1.42	−1.14
	10+	0.29	4.69	12.36	8.67	0.59	10.15
Severe	1–2	−1.51	−1.16	−1.36	−1.16	−1.05	−0.60
	3–5	−1.42	−1.45	−1.42	−1.55	−1.03	−0.99
	6–10	−0.98	−0.90	−1.21	−0.77	−0.98	−0.95
	10+	−0.77	0.55	−0.09	3.99	−1.06	5.68
Extreme	1–2	−0.66	−0.97	−0.47	1.20	−1.07	−0.25
	3–5	−0.99	−1.24	−0.81	−0.73	−1.24	−1.13
	6–10	−1.32	−0.96	1.33	0.09	−1.34	4.52
	10+	−0.42	−0.74	0.36	0.41	2.04	1.21

5. Conclusions

The social and environmental impacts of CDHEs, in which drought and hot events occur simultaneously, are greater than the impacts of individual events. In this study, the SPI and maximum temperature were used to define CDHEs on the daily scale, hot spot areas were identified and the characteristics and changes in the multiple aspects of CDHEs were explored in order to mitigate their adverse effects. The main conclusions are as follows:

There was an upward trend in most areas from the north to the southwest and a downward trend in most of the northwestern and southeastern regions for the number of CDHDs. NC and SWC are high-frequency regions of CDHDs, and the number of CDHDs and land area ratio affected by CDHDs were increasing, which may have greater adverse effects. Thus, these two regions were selected as hot spot areas for more detailed analysis.

CDHEs have become more frequent, long-lasting and extreme in eastern China. The frequency of CDHEs tended to rise in most regions from the north to the southwest, and was higher than that in the other regions. The duration of CDHEs was longer in the southern region than in the northern region, with longer duration from the northern to southwestern regions. CDHEs of all durations and severities generally showed an increasing trend, with the characteristics of being mostly below normal until the early 1990 s and mostly above normal thereafter. Comparing the contribution of CDHEs with different severities / durations to the total CDHEs in the two periods, it was found that the CDHEs become more extreme and persistent, especially in NC. Although the change in SWC is not as great as that in NC, both extreme and long-duration events contribute more to the total CDHEs in SWC than in the other regions.

The possible occurrence dates of CDHEs during the warm season were from early May to early October (the entire eastern China), early May to late September (NC), and early May to mid-October (SWC), respectively. The shapes of the probability distribution were similar for the different severities. The probability distribution of occurrence date was unimodal in the entire eastern China and it was similar in NC. Whereas, the probability distribution was bimodal in SWC. Compared with 1961–1990, most of the occurrence dates of CDHEs with different severities in 1991–2018 postponed, and this feature in SWC was the most pronounced.

CRediT authorship contribution statement

Mengyang Liu: Conceptualization, Data curation, Formal analysis, Methodology, Software, Validation, Writing – original draft. **Yixing Yin:** Software, Investigation, Project administration, Resources, Supervision, Writing – review & editing. **Xiaojun Wang:** Funding acquisition, Investigation, Project administration, Resources, Supervision. **Xieyao Ma:** Funding acquisition, Investigation, Project administration, Resources, Supervision. **Ying Chen:** Supervision, Writing – review & editing. **Weilin Chen:** Writing – review & editing.

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.

Data availability

Data will be made available on request.

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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.2022.128499.

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