



Spatial compounding of droughts and hot extremes across southwest and east China resulting from energy linkages

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ABSTRACT

The concurrence of droughts and hot extremes at the same location can lead to immense damages to water resources, agriculture, and ecosystems. However, assessment of simultaneous occurrences of the two extremes at multiple regions, which can lead to amplified impacts due to socioeconomic linkages such as energy transmission, has been limited. In this study, we first demonstrated the characteristics of this type of compound extremes based on droughts in Southwest China (SC) and hot extremes in East China (EC) during 2022. We then evaluated changes in the frequency and duration of this type of compound extremes in historical periods from 1979 to 2022. Finally, we projected changes in these characteristics during the future period (2025–2044) based on simulations from the Coupled Model Intercomparison Project Phase 6 (CMIP6). Results showed that droughts in the SC (associated with hydropower losses) and hot extremes in the EC (associated with surging electricity) peaked in July–August 2022, which constituted the spatially compounding droughts and hot extremes (CDHEs). For the historical period, the spatial CDHEs have occurred several times, including the summer of 1994, 2006, 2016, and 2022. Future projections showed that the frequency and duration of this type of CDHEs may increase in the future compared with the rare occurrences in historical periods, which largely results from substantial increases in hot extremes in EC. This study provides useful insights into the adaptation measure of compound droughts and hot extremes in China, which can be beneficial for energy security in a changing climate.

1. Introduction

Multiple weather and climate extremes can cause severe impacts on different sectors (usually termed compound extremes) and have been a growing cause for concern (IPCC, 2021; Zscheischler et al., 2020). These extremes manifest in different types, including preconditioned, multivariate, temporally compounding, and spatially compounding (Zscheischler et al., 2020). For example, a specific type of extreme may occur concurrently across multiple locations causing disastrous impacts, which is often termed spatially compounding extremes (Bevacqua et al., 2021; Zscheischler et al., 2020). Under global warming with an overall increase in the frequency and intensity of climate extremes across multiple regions (IPCC, 2021), there is a tendency towards increased risk of co-occurrences of extremes at different regions, calling for an improved understanding of the spatially compounding extremes for the design of adaptation measures.

Droughts and heatwaves are two high-impact natural hazards with

significant impacts on multiple sectors including agriculture (Lesk et al., 2022), ecosystems (Li et al., 2022), wildfire (Sutanto et al., 2020), hydropower or energy security (Liu et al., 2023; Otero et al., 2023; Su et al., 2020), and human health (Zeighami et al., 2023). Droughts (or heatwaves) can occur simultaneously at multiple locations, leading to spatially compounding droughts (or hot extremes) (Kornhuber et al., 2023), which can induce larger impacts than the individual extreme (Anderson et al., 2018; Anderson et al., 2019; Singh et al., 2022). For example, apart from a wide range of impacts from preconditioned droughts (or drought propagation) (Zhang et al., 2022), multivariate droughts (Hao et al., 2018), and temporally compounding droughts (or multi-year drought) (van der Wiel et al., 2023), the spatially compounding droughts at multiple breadbaskets can cause synchronous shocks in food supply, posing challenges to the regional or global food systems (Muthuvel et al., 2023; Singh et al., 2021). Verschuur et al. (2021) found that the concurrent droughts in Lesotho and South Africa during 2007 led to synchronous crop production failure, causing

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disastrous impacts to the socioeconomics. The occurrence of the spatially compounding extremes can be related to large-scale drivers, such as El Niño-Southern Oscillation (ENSO) or Rossby waves. For example, concurrent drought occurrences in agricultural regions across North/South America and Australia can be related to the ENSO (Anderson et al., 2018; Anderson et al., 2019; Singh et al., 2022), or other large-scale drivers, such as Indian Ocean Dipole (IOD) (Singh et al., 2021). In addition, simultaneous occurrences of heatwaves at multiple locations might result from the circum-global Rossby waves across the mid-latitudes of the Northern Hemisphere (Kornhuber et al., 2020).

Previous studies have assessed the spatially compounding extremes of either droughts or hot extremes at multiple locations. These two extremes can also occur simultaneously at the same location, which is usually termed compound droughts and hot extremes or heatwaves (CDHEs or CDHWs), leading to the multivariate type of compound extremes (Hao et al., 2022). Meanwhile, the spatial compounding of droughts and hot extremes can also relate to droughts and hot extremes at different locations due to the large-scale atmospheric and oceanic drivers, leading to the spatial compounding of extremes (Rodrigues et al., 2019). One such example is the co-occurrence of terrestrial droughts in California and marine heatwaves in the northeast Pacific during 2013–2014 (with the impact on marine productivity, water supply, and economic losses in fisheries and agriculture), which was driven by persistent upper troposphere atmospheric ridges and anomalous sea level pressure over the northeast Pacific (Shi et al., 2021). In addition, spatially compounding droughts and hot extremes can be formed due to the socioeconomic linkage across multiple sectors or regions (e.g., supply/demand chains). For example, the drought impact in one location can cause ripple effects on different sectors of other locations (e.g., reduced hydropower generation at local scale and outbound transmission), which can amplify the impact of hot extremes in other locations. However, this type of spatially CDHEs across multiple regions has been less explored.

The objective of this study is to investigate the concurrences of droughts in Southwest China (SC) and hot extremes in East China (EC) in historical and future periods. The monitoring of droughts in SC and hot extremes in EC from June to September 2022 was performed based on observations to demonstrate the risk of such spatially CDHEs. In addition, changes in the frequency and maximum duration of the spatially CDHEs during the historical period (1979–2022) were explored. We then extended our analysis to the projection of the spatially CDHEs in the future period (2025–2044) based on CMIP6 model simulations.

2. Data and methods

2.1. Data

The spatially CDHEs during the summer period (June–July–August, JJA) were assessed using monthly precipitation, monthly average temperature, and daily maximum temperature data based on observations and model simulations. These data for the historical period from 1979 to 2022 were obtained from the CN05.1 dataset with a spatial resolution of 0.25×0.25 degrees (Wu and Gao, 2013). In addition, future projections of spatially CDHEs across southwest China and east China (SC and EC) were assessed using data from Coupled Model Inter-comparison Project 6 (CMIP6) model simulations (Eyring et al., 2016). For this study, simulations from 16 CMIP6 models with relatively high resolutions under the SSP5-8.5 scenario were selected (Table S1) for the near future period from 2025 to 2044 (to compare with the results of the baseline period 1995–2014). We used a single member of each model for comparisons (r1i1p1f1). The bilinear interpolation method was applied to re-grid the CMIP6 data into a spatial resolution of 1×1 degree.

2.2. Droughts and hot extremes

We computed the Standardized Precipitation Index (SPI) as the drought indicator for tracking drought severity in historical periods. The drought event was defined when the SPI index is less than or equal to -0.5 (i.e., $SPI \leq -0.5$), which corresponds to precipitation lower or equal to the 30th percentile. Similar to SPI, the Standardized Temperature Index (STI) based on monthly average temperature was used to monitor hot extremes during each summer month for the historical period (1979–2022). In addition, we use the 90th percentile of the daily max temperature of each summer month to compute the daily hot extremes. Specifically, the frequency of hot extremes was defined when the number of days with daily max temperature higher than the temperature threshold (i.e., $T > T_{90}$) (Perkins, 2015) and the max duration of hot extremes was defined as the maximum length of consecutive days of hot extremes. For the future projection, we use the 30th percentile of monthly precipitation and 90th percentile of daily max temperature as thresholds to define the drought (i.e., $P < P_{30}$) and hot extremes (i.e., $T > T_{90}$) using the base period 1995–2014 for computing relative thresholds.

2.3. Definition of spatially CDHEs

Here we selected Sichuan province in Southwest China (SC) and the Yangtze River Delta region (Shanghai, Jiangsu, Zhejiang, and Anhui) in East China (EC) as study areas to define the spatially CDHEs, as shown in Fig. 1. Sichuan Province is the largest hydroelectric power generation province in China, which is an important base for “West-East Power Transmission”. The installed hydropower capacity accounts for more than 80 % of the total power generation of the province, with nearly one-third of the annual hydropower generation exported, for which the East China Power Grid (ECPG) is one of the main regions of electricity consumption (Hu et al., 2016; Li et al., 2018). Since a large portion (>60 %) of the hydropower capacity in Sichuan Province is from run-of-river hydropower plants (Zhou et al., 2023), extreme droughts can significantly affect the hydropower production in SC. Several provinces in EC (Shanghai, Jiangsu, Zhejiang, and Anhui provinces) within the coverage of ECPG are among the receivers of hydropower from Sichuan Province, thereby being vulnerable to droughts in SC.

We define the spatially CDHEs as the simultaneous occurrences of droughts in SC and hot extremes in EC, where the compounding impacts are induced through the linkage of hydropower transmission. To explain the linkage involved in this type of spatially CDHEs, we demonstrate the relationship between hydropower electricity supply and demand in Fig. 2. For hydropower supply, when the reservoir generates a head difference with the downstream, hydraulic potential can be converted into hydropower (using turbines and generators), which is consumed locally (i.e., SC in this study) or transported to other regions (i.e., EC in this study). For example, hydropower from SC is transported through long-distance ultra-high-voltage transmission lines (to the ECPG) to users in EC (Zhou et al., 2010). When extreme droughts occur in SC, substantial power generation capacity will be lost due to lowered reservoir water level. When hot extremes bring an increase in electricity demand in EC, the reduced hydropower generation in SC adds another layer of vulnerability to the electricity supply and demand in EC. Note that extreme heat can also result in an increase in high-voltage transmission losses and even line deterioration, triggering power supply disruptions.

2.4. Computation of spatially CDHEs

Based on the monthly precipitation and temperature, the spatially CDHEs were defined when SPI in SC was lower than (or equal to) -0.5 and the STI in EC was higher than 0.5 ($STI > 0.5$), which was employed to monitor the compound extreme at the monthly time scale during summer. For the summer season (JJA), the frequency of the spatially

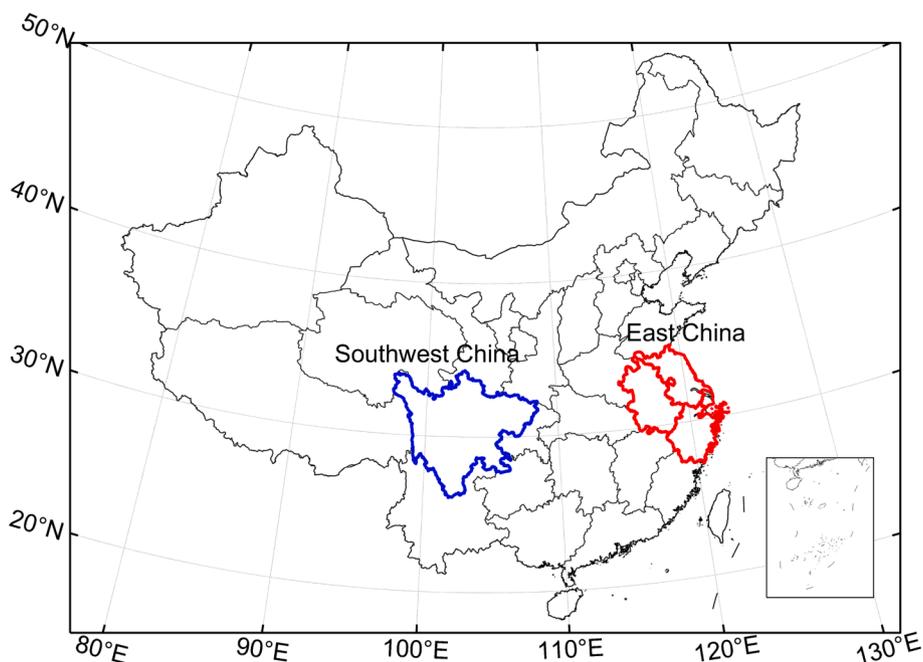


Fig. 1. Study areas of Sichuan Province in Southwest China (SC) and East China (EC).

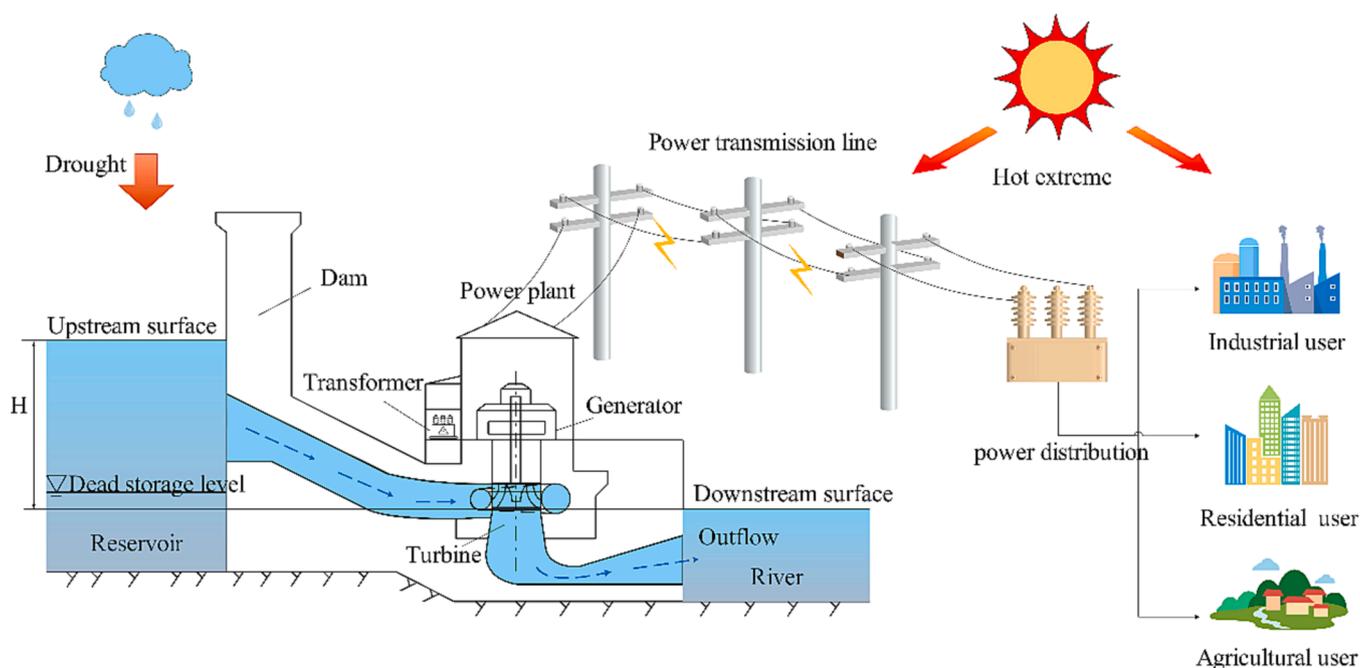


Fig. 2. Conceptual diagram of the spatial compounding of droughts and hot extremes across different regions due to energy linkage.

CDHEs was defined as the number of days with daily temperature exceeding the 90th percentile in EC when droughts occur simultaneously in SC ($SPI \leq -0.5$ or $P < P30$). In addition, the maximum duration of the spatially CDHEs for each month was obtained as the longest consecutive days of temperature exceeding the 90th percentile in EC with the concurrence of drought in SC.

3. Results

3.1. Monitoring the 2022 events

The concurrent droughts and hot extremes during summer 2022 in

the Yangtze River Basin led to significant socioeconomic losses (Hao et al., 2023). To demonstrate the risk of spatially CDHEs, we first investigated the evolution of droughts in SC, hot extremes in EC and their concurrence in 2022. The development of drought (based on SPI) in SC from June to September 2022 is shown in Fig. 3 (a-d). The drought began in the northeastern regions in June and the spatial extent extended to most parts of the region in August, which is consistent with previous studies (Ma et al., 2022b). The severity of droughts became the strongest in July. For example, in July, the average value of SPI in SC was -1.5 while the average SPI was -0.07 and -0.88 in June and August, respectively. In September, drought recovery was witnessed in western regions with moderate drought conditions prevailing in the

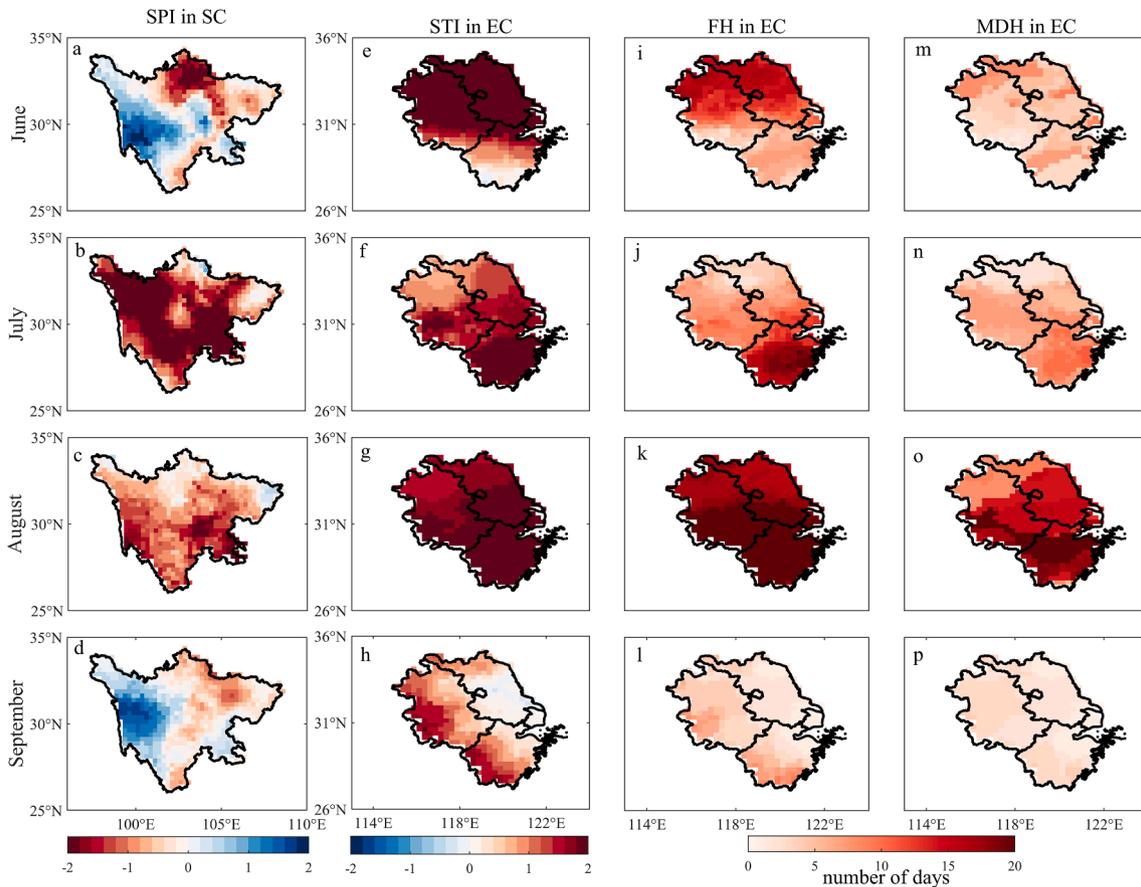


Fig. 3. Monitoring of droughts in SC (a-d) and hot extreme in EC (e-p) from June to September 2022. FH and MDH represent the frequency and the maximum duration of hot extremes, respectively.

eastern parts.

The development of hot extremes (based on STI) from June to September in EC was displayed in Fig. 3 (e-h), with the frequency and maximum durations shown in Fig. 3 (i-p). The northern EC experienced hot extremes in June. For instance, the average severity was 2.15 in the northern region. The hot extremes mostly resided in the southern parts of EC in July and continued to develop in August, with spatial extent expanding to most of the EC in August (Zhang et al., 2023). For example, the maximum duration in the southern region reached around 20 days in August. By September, the hot extremes weakened with slight positive high-temperature anomalies in the southern regions.

The severe drought in SC (associated with reduced hydropower) and high temperature in EC (associated with surging electricity demand) constitute the spatially compounding droughts and hot extremes due to potential impacts on or risk to the electricity balance. For instance, owing to the persistent rainfall deficits in the summer of 2022, the major basins in SC were struck by severe droughts in its rainy season, resulting in a significant reduction in hydropower generation in SC. The reduced hydropower can affect the outward transmission of hydroelectric power to other regions (including EC). At the same time, the hot extremes in EC led to soaring power loads on the power grid. Consequently, the reduced hydropower production in (and transmission from) SC and electricity demand from the extremely high temperature in EC collectively brought severe risks to energy users in EC.

3.2. Historical patterns and changes

The extreme droughts in SC and high temperatures in EC in 2022 raise a question as to the occurrence of this type of compound extremes across the two regions during historical periods (1979–2022). We first

demonstrated the occurrences of spatially CDHEs using SPI and STI during summer, as shown in Fig. 4. This type of compound extreme has occurred in historical periods, including the summer of 1994, 2006,

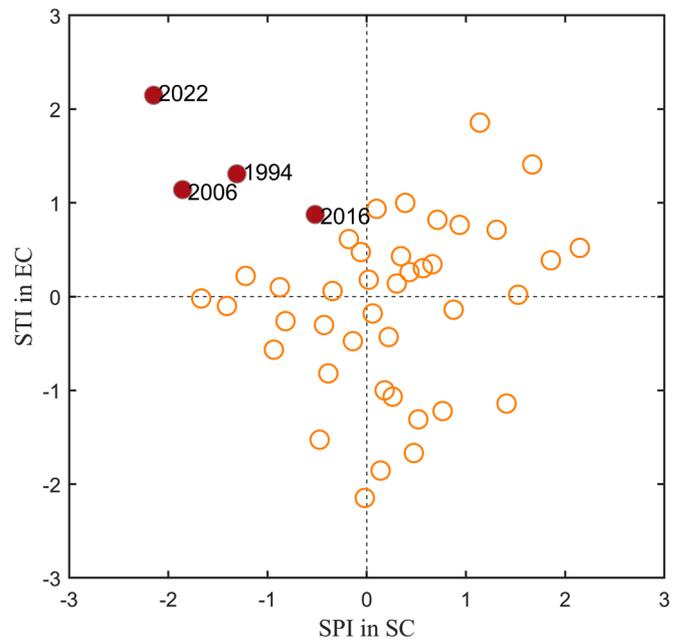


Fig. 4. Scatter plot of SPI (droughts) in SC and STI (hot extremes) in EC during summer for the historical period from 1979 to 2022. Severe events during 1994, 2006, 2016, and 2022 are represented by solid dots.

2016, and 2022. The 2022 drought and hot extreme is a record event, with the lowest SPI and highest STI. The spatially CDHEs in 1994 and 2006 were also severe events. For example, in 2006, the average SPI in SC and STI in EC were -1.90 and 1.14 , respectively.

To further show the co-evolution of droughts and hot extremes across the two regions, we explored the frequency and duration of this type of compound extremes, as shown in Fig. 5. Severe droughts occurred in the SC region in historical periods, such as 1994, 2006, 2011, 2016, and 2022, which are consistent with previous studies (Liu et al., 2021; Xia et al., 2022). Hot extremes also occurred in EC during the summer of 1988, 1994, 2013, 2016, 2017, and 2022, as confirmed in previous studies (Ding et al., 2018; Sun et al., 2014; Wang et al., 2018; Wang et al., 2023). From a compound event perspective, many of these drought events in SC were accompanied by high temperature anomalies in EC. For instance, for the compound extremes in 1994 and 2016, the frequency of spatially CDHEs was higher than 15 days and the maximum duration was longer than 9 days. The 2022 events hit the record with the highest frequency (44 days) and longest (maximum) duration (23 days).

To assess the changes in the frequency and maximum duration of CDHEs in the historical period, the characteristics of CDHEs for 11-year periods (i.e., 1979–1989, 1990–2000, ...) were calculated, as shown in Fig. 6. Overall, we found an increase in the frequency and maximum duration of the spatially CDHEs, especially after the 1990 s. For example, the maximum duration of CDHEs has increased from 15 days

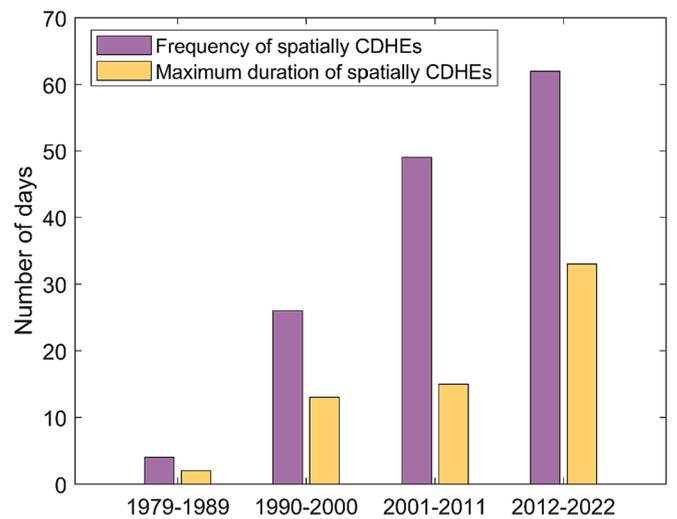


Fig. 6. Historical changes in the frequency and maximum duration of the spatially compounding droughts (in SC) and hot extremes (in EC) for the historical period from 1979 to 2022.

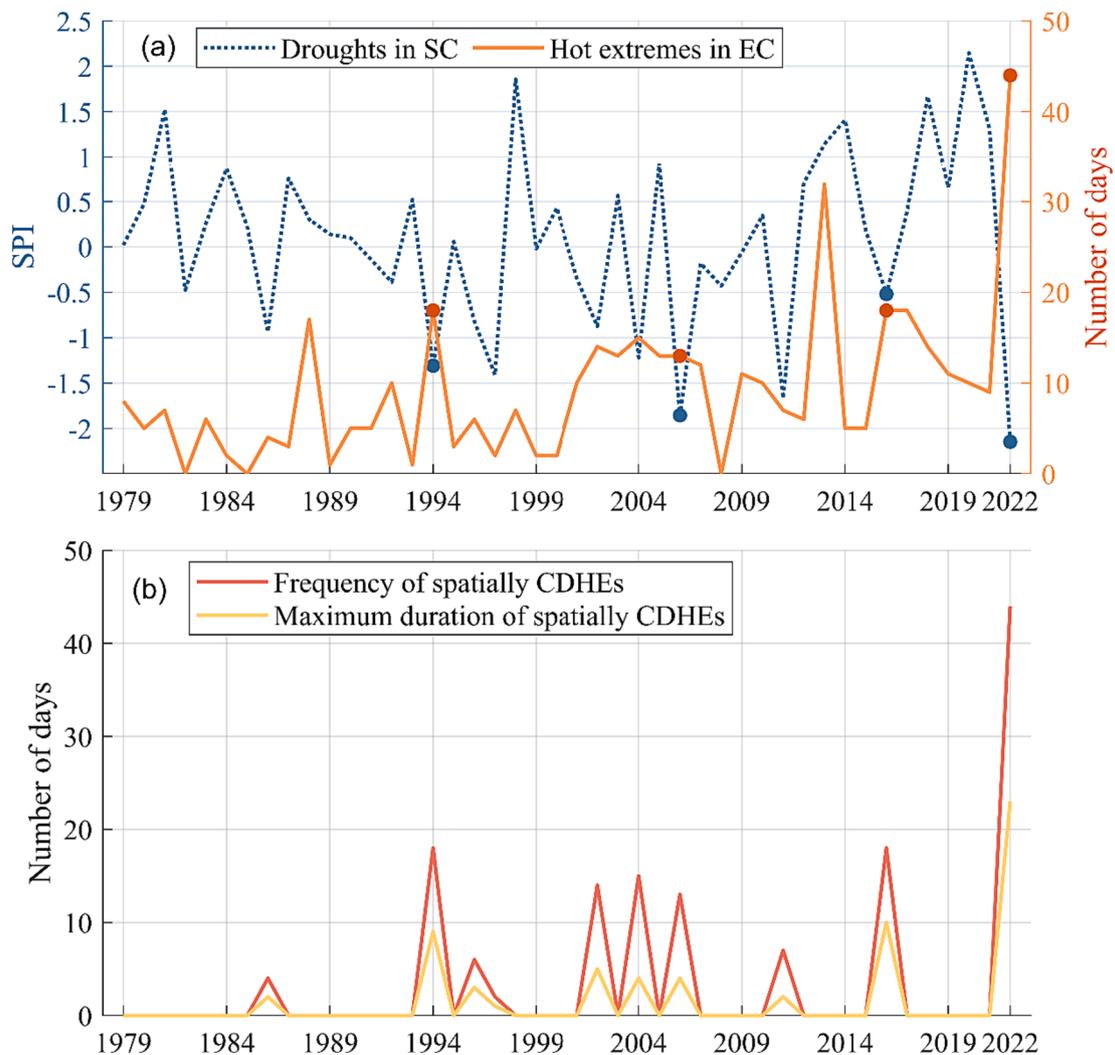


Fig. 5. Time series of SPI in SC (frequency of hot extremes in EC) (a) and frequency/maximum duration of spatially CDHEs (b) during the historical period from 1979 to 2022. The solid dots in (a) represent four cases of spatially CDHEs during 1994, 2006, 2016, and 2022.

in 2001–2011 to 33 days in 2012–2022. The increase in the spatially CDHEs across SC and EC regions in the historical period draws our attention to their potential changes in the future, which will be explored in the following section.

3.3. Future projection

The spatial characteristics of droughts and hot extremes during 2025–2044 were compared with those during 1995–2014 to evaluate projected changes in drought frequency in SC and frequency/maximum duration of hot extremes in EC, as shown in Fig. 7. For the spatial changes of drought in SC, most of the grid points (except for the southwestern parts) were projected to experience a decrease in drought frequency in the summer of the future period (2025–2044), which is consistent with the increase of precipitation in the near future (Wang et al., 2014). For the spatial changes of hot extremes in EC, the frequency and maximum duration of hot extremes were projected to increase in the future (Ma et al., 2022a; Yang et al., 2021). The boxplots of changes in drought frequency and hot extreme frequency/maximum duration based on 16 CMIP6 simulation models are shown in Fig. 8(a). The relative change in drought frequency in the SC region has great uncertainty, with the changes ranging from -42 % to 14 % (for the 25th to 75th percentile). The frequency and maximum duration of high-temperature extremes in EC were projected to increase remarkably, ranging from 89 % to 174 % and 44 % to 149 % (for the 25th to 75th percentile), respectively. In summary, droughts in SC were projected to

decrease and the frequency/maximum duration of hot extremes in EC were projected to increase for the future period from 2025 to 2044.

We further investigated changes in the spatially CDHEs in the summer of the future period 2025–2044 (relative to 1995–2014), as shown in Fig. 8(b). A salient pattern is that the frequency and maximum duration of spatially CDHEs were projected to increase in the future period (with 149 % and 113 %, respectively). This indicates a higher likelihood of the spatial compounding of SC droughts and EC hot extremes. Based on individual changes in Fig. 8(a), the increase in the spatially CDHEs in the future is likely driven by the increase in hot extremes. This implies that, although there are uncertain changes in drought frequency (based on precipitation only), the frequency/duration of spatially CDHEs in SC and EC may increase remarkably in the future. These findings heighten the importance of coping with the high risk of the spatially CDHEs in the future.

4. Discussion

4.1. Implication

The simultaneous occurrences of droughts and hot extremes in the same location, which can cause amplified effects on the natural ecosystems or society, have been widely evaluated (Hao et al., 2022). The combined impact of the two extremes may not only manifest in the same location but also exert pressure across different regions due to the socio-economic linkages (e.g., hydroelectric power transmission). Building on

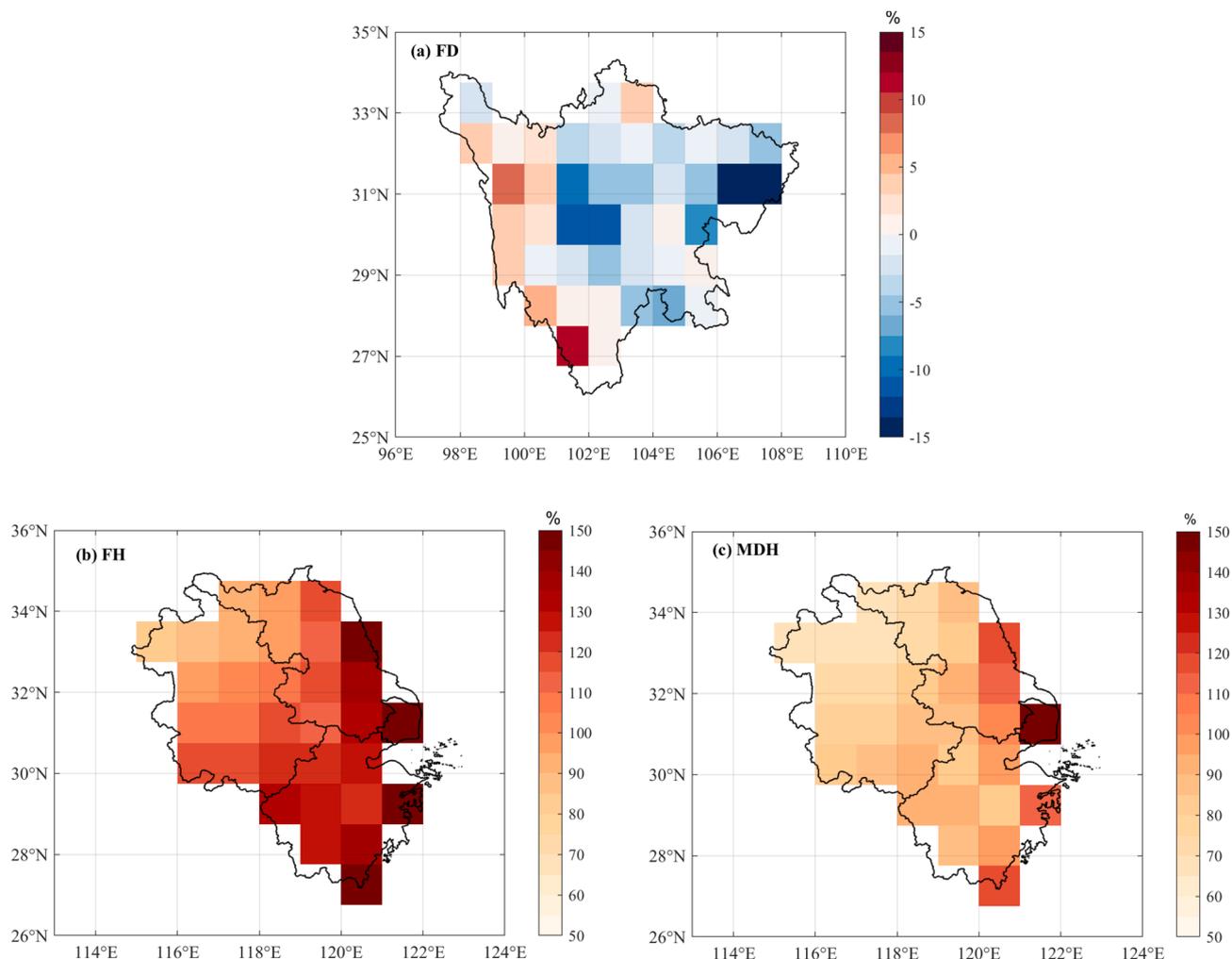


Fig. 7. Relative changes in the frequency of droughts (FD) (a) and frequency/maximum duration of hot extremes (FH/MDH) (b-c) for the future period 2025–2044 relative to 1995–2014.

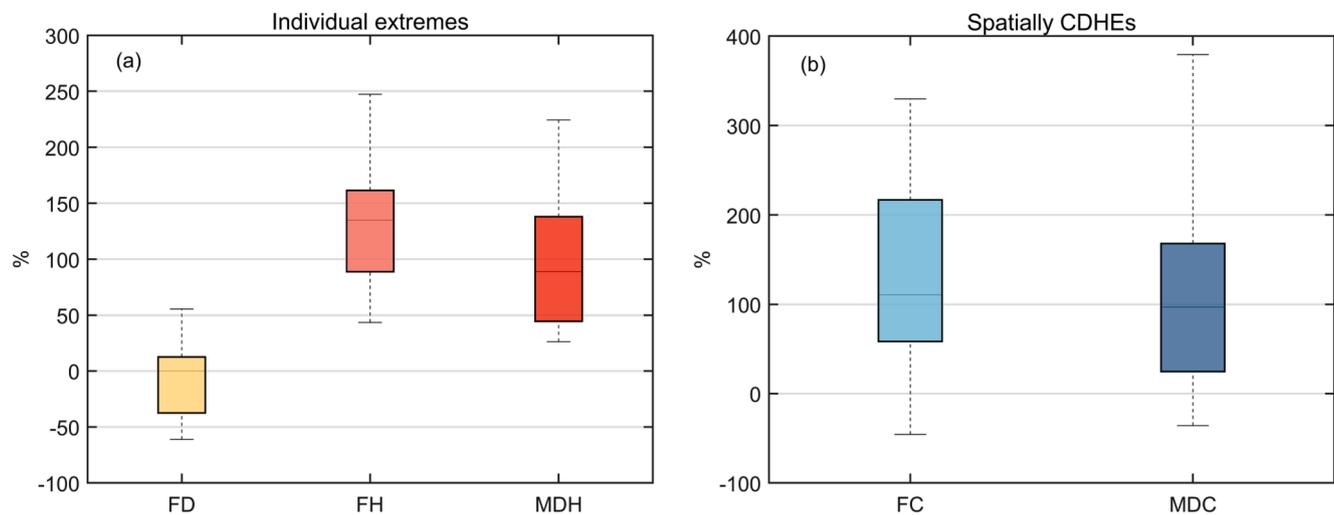


Fig. 8. Boxplots of relative changes in the individual droughts/hot extremes (a) and spatially CDHEs (b) in the future period 2025–2044 relative to 1995–2014. FD and FH/MDH represent the frequency of droughts and frequency/maximum duration of hot extremes, respectively. FC and MDC represent the frequency and maximum duration of spatially CDHEs. Droughts and hot extremes are computed based on the regional averaged precipitation and high temperature across all grids.

this concept, here we defined a type of compound droughts and hot extremes in different regions consisting of drought-induced hydropower reduction at one region and heatwave-induced energy demand in another region, where hydroelectricity transmission exists between the two regions. The demonstration of the increased likelihood (or risk) of this type of spatially compound extremes in future periods across SC and EC implies the urgent need for coping with these extremes.

Suitable adaptation measures should be devised to reduce the potential impacts of this compound extreme, such as the monitoring or forecasting systems of compound extremes and development of hybrid power systems. For example, suitable indicators of the spatially CDHEs (e.g., based on impacts or joint distributions) should be developed to track their evolutions. Accurate prediction of droughts (or streamflow) in the hydropower region (reflecting energy supply or shortage) and heatwaves of the same location (reflecting the local energy demand) and other locations with hydropower transmission (reflecting remote energy demand) can be a useful endeavor to help prepare for the potential impacts of compound extremes. To provide such early warning information, an improved understanding of the physical mechanism of concurrent droughts (heatwaves) in the SC region and heatwaves in EC is needed, which should be further investigated in future studies. In addition, the combined effect of drought-induced hydropower reduction and increased electricity demand due to heat waves may force power system operators to resort to fossil fuel power plants to mitigate the impacts (Zeighami et al., 2023). In this case, coal will still be expected to play a pivotal role, making it more challenging to meet the carbon peak and carbon neutrality goals. This calls for the development of hybrid hydropower, wind, and solar power systems with more grid flexibility and investments in power storage measures.

This type of compound extremes also presents growing challenges for investigating compound extremes based on climate models, such as model evaluation and assessing their impacts or risks. For the evaluation of model performances in simulating extremes, we should not only focus on droughts and hot extremes at the same location but should also pay attention to the extremes at different locations. In addition, for the assessment of the impact or risk of compound extremes under global warming, we should also look into combined impacts from extremes across multiple sectors or regions (IPCC, 2022). In this regard, along with the increasing efforts in the understanding and modeling of compound extremes consisting of discrete climate hazards, this study demonstrates that compound risks can result from the climate and non-climate drivers and the impact at one location can be transmitted to remote locations through physical or socio-economical pathways, as

conceptualized in previous research (Simpson et al., 2023; van den Hurk et al., 2023). Addressing the challenges of the impact or risk across regional boundaries (and/or sectorial boundaries) requires the analysis framework that adopts the systematic risk approach (e.g., definition of system boundaries, risk propagation mechanisms, quantitative impact evaluations) and factors into complex interactions among hazards, exposures, and vulnerabilities (Carter et al., 2021; van den Hurk et al., 2023).

The spatial compounding of droughts and hot extremes proposed in this study also provides insight into the classification of different CDHEs. As stated previously, four types of compound extremes, including pre-conditioned, multivariate, temporally compounding, and spatially compounding, have been defined (Zscheischler et al., 2020). Traditionally, droughts and hot extremes are mainly defined as the concurrence at the same location (or multivariate type). Along with the spatial compounding of droughts and hot extremes across different regions defined in this study, other types of CDHEs also need further exploration to avoid or reduce their potential impacts. For example, drought induced hot extremes, which is usually related to the soil moisture deficit-temperature interactions (Hao et al., 2017; Mueller and Seneviratne, 2012; Mukherjee et al., 2023; Páscoa et al., 2022), can be regarded as the pre-conditioned type of CDHEs. Moreover, the prolonged periods of droughts followed by warm (and wet) periods (e.g., months or seasons) can cause higher impacts, such as disease transmission (Lowe et al., 2021), which can be regarded as the temporal compounding of droughts and hot extremes. The extended definition of compound droughts and hot extremes (or hot droughts), as demonstrated in this study, can help raise awareness and understanding of the effects of CDHEs, thereby facilitating some adaptation to climate change.

4.2. Limitation

The limitation of this study includes the insufficient representation of hydropower generation and simplification of local or regional response during energy shortages. Due to the limited data availability, we use meteorological droughts in SC to represent hydropower deficits in the source region. This may lead to large uncertainty in the characterization of hydropower generation or reduction since meteorological droughts may not always lead to hydropower deficits due to the complicated drought propagation process and influences of human activities (reservoir regulation) (Zhang et al., 2022). In the future, the estimation or representation of hydropower generation in SC can be improved based on hydrological simulations (Liu et al., 2016). In addition, the omission

of other factors that may affect the electricity supply in the source region or demand region can be another limitation. For example, during the drought-induced hydropower reduction (or electricity shortage) in SC, the State Grid dispatched electricity supply from other regions (e.g., northwest China) to SC, which may increase the energy supply in this region. Nevertheless, if large-scale droughts (and/or heatwaves) sweep a large portion of China, the dispatch of hydroelectricity from other regions (e.g., experiencing drought-induced hydropower losses) may not be sufficient for the electricity demand. This highlights the need to consider the spatial compounding of droughts/heatwaves across China, especially in regions with hydropower production.

Note that our analysis is based on the assumption that the reduced hydropower in SC can cause reduced hydropower transmission to EC. In reality, due to the complex governance and management, this assumption may not hold due to the cross-provincial power transmission contract. Nevertheless, this study highlights the potential risk to the electricity in EC due to droughts in remote regions, which needs further analysis in a quantitative manner to ensure energy security. In addition, although we focus on the risk of electricity crunch in EC due to the spatially CDHEs, the concurrent droughts and hot extremes in the SC also influenced the electricity supply locally due to drought-induced hydropower reduction and heatwave-induced increase in electricity demand, causing rolling blackouts associated with power shortage and affecting industry production (Hao et al., 2023), which may further complicate the risk of the spatial compounding of droughts in SC and hot extremes in EC. Last but not least, the findings of this study are subject to uncertainties associated with extreme thresholds and projection periods, the selection of which may lead to differences in extremes and their changes.

5. Conclusions

This study proposed a type of compound droughts and hot extremes through the impacts on electricity balance resulting from droughts and hot extremes in remote regions with hydropower transmission. We first demonstrated this case with the drought in SC (leading to reduced hydropower) and hot extremes in EC (leading to increased electricity demand) in the summer of 2022. We then analyzed the characteristics of this type of CDHEs in historical periods and projected their changes in the future period. The following conclusions can be drawn from this study.

- (1) In the summer of 2022, the drought in SC and hot extremes in EC began in June and expanded to most parts of the regions in July and August. In July, the severity of the drought in SC became the strongest while the hot extremes in EC continued to develop in August.
- (2) The spatially CDHEs have occurred during the historical period (1979–2022), such as the summer of 1994, 2006, 2016, and 2022. The spatially compounding of droughts in SC and hot extremes in EC during 2022 was a record event. A substantial increase in frequency and duration of spatially CDHEs after the 1990s was observed.
- (3) For future periods (2025–2044), the multi-model average from CMIP6 projections showed a significant increase of 149 % and 113 % in the frequency and maximum duration of spatially CDHEs, respectively, compared to the historical period (1995–2014). This is likely driven by a significant increase in hot extremes in EC.

Due to the high impact of this type of compound extremes, adaptation measures, such as early warning systems, should be devised in the future. To achieve this goal, it is necessary to improve the understanding of the mechanisms that drive droughts and heat waves in remote regions. Moreover, a systematic risk approach is needed to diagnose the physical or socio-economical pathways of the impact or risk transmitted

to remote locations, thereby understanding the impact or risk cascading across sectors and regions. The findings of this study can provide useful information for the decision-making of droughts/heatwaves management and electricity dispatch from a compound event perspective.

CRedit authorship contribution statement

Boying Lv: Data curation, Formal analysis, Writing – original draft. **Zengchao Hao:** Conceptualization, Formal analysis, Supervision, Writing – original draft, Writing – review & editing. **Qian Ma:** Formal analysis. **Yang Chen:** Formal analysis. **Xuan Zhang:** Formal analysis. **Yongshuo Fu:** Formal analysis. **Fanghua Hao:** Formal analysis.

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

I have shared the link of data in the manuscript.

Acknowledgments

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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.2024.130827>.

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