



Compound droughts and hot extremes: Characteristics, drivers, changes, and impacts

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ABSTRACT

Compound droughts and hot events or extremes (CDHEs) may lead to larger repercussions than do individual extremes. Due to the disastrous impacts and increased risk of these events under global warming, increased attention has been paid to them from both research and operational communities. This review provides a synthesis of the literature on characteristics, drivers, changes (detection, attribution, and projection), and impacts of CDHEs. Different characteristics of these events (e.g., frequency, duration, and spatial extent) are first introduced based on drought and hot indicators at different time scales. We then summarize multiple physical mechanisms of CDHEs, including the atmospheric circulation (and modes of variability) and land-atmosphere feedbacks across different regions. Evidence from observations shows an overall increase in CDHEs in the past few decades at regional and global scales, which mainly results from an increase in hot extremes and is likely attributable to anthropogenic influences. Future projections indicate an increase in CDHEs over most global land areas. Quantitative assessments of the impact of CDHEs on different sectors (e.g., water resources, crop yield, vegetation) highlight their amplified impacts compared with individual droughts or hot extremes. Several challenges in the data availability, characterization, physical mechanism, simulation, and impacts of CDHEs and opportunities to address these challenges are then discussed. This study can be useful for better understanding, modeling and risk analysis of compound extremes under global warming.

1. Introduction

Global warming manifests in increased temperature and shifted precipitation regimes, which are associated with an increase in the frequency and intensity of weather and climate extremes (Coumou et al., 2013; Hansen et al., 2010; Jones et al., 1999; La Sorte et al., 2021; Stocker et al., 2013), including droughts and hot extremes (Baldwin et al., 2019; Dai, 2013; Gebremeskel Haile et al., 2019; Naumann et al., 2018; Perkins et al., 2012; Trenberth et al., 2014). Increased weather and climate extremes may induce huge repercussions on the ecosystem and society, hindering progress towards sustainable development goals. For example, increased droughts and hot extremes may deplete water resources, impair agriculture production, damage ecosystems, increase energy demand, amplify wildfire risk, and affect human health (Ciais et al., 2005; Schewe et al., 2019; Vicente-Serrano et al., 2020b; Vogel et al., 2021a; Watts et al., 2015). Thus, it is important to improve our

understanding and modeling of climate extremes and their impacts.

A plethora of research has shown that combined extremes (e.g., droughts and hot extremes) may lead to adverse impacts on water supply, crop yield, and livestock mortality, which can be higher than the sum of their counterparts (Chen et al., 2018; García-Herrera et al., 2010; Seneviratne et al., 2021; Teuling, 2018; Ward et al., 2022). This phenomenon of large impacts from multiple variables, which refers to the extremes occurring at the same or different locations with or without a time lag, is commonly termed “compound events” (Hao et al., 2013; Leonard et al., 2014; Seneviratne et al., 2012; Seneviratne et al., 2021; Zscheischler et al., 2018). Note that there are other terms describing similar phenomena of compound events, including combined, cascading, contemporaneous, coincident, simultaneous, concurrent, or consecutive events or extremes (Cutter, 2018; de Ruiter et al., 2020; Drakes and Tate, 2022; Gill and Malamud, 2014; Hao et al., 2013; Hillier et al., 2020; Kappes et al., 2012; Pescaroli and Alexander, 2018;

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Schauwecker et al., 2019; Tilloy et al., 2019).

Compound events are first defined in IPCC special report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) in 2012, which can be of different types (Seneviratne et al., 2012):

“(1) two or more extreme events occurring simultaneously or successively, (2) combinations of extreme events with underlying conditions that amplify the impact of the events, or (3) combinations of events that are not themselves extremes but lead to an extreme event or impact when combined”. While the first and third component of the definition is relatively straightforward, the definition of the second type of events (e. g., underlying conditions) is less clear. Firstly the underlying conditions can be interpreted as a mere amplification of an existing compound event and secondly they could also be understood as parts of the compound event (Leonard et al., 2014). Recently, Zscheischler et al. (2018) defined compound events as “the combination of multiple drivers and/or hazards that contributes to societal or environmental risk”, which is used in the latest IPCC AR6. Following Seneviratne et al. (2021), we use this definition of compound events in this study, as it focuses on the risk framework in IPCC and highlights the drivers of compound events are not necessary to be dependent. Here the drivers refer to weather/climate processes, variables, or phenomena spanning multiple temporal-spatial scales and the hazard (also termed “climate impact-drivers”) can be potential occurrences of natural or human-induced events or trends causing health impacts (e.g., losses of life, injury) as well as loss and damage to the property, infrastructure, ecosystems, environmental resources and other sectors (Field et al., 2012; Masson-Delmotte et al., 2021). Hazards can be caused by one or more climate drivers and the risk here is defined as the product of the probability of hazards and consequences (unfolding as a combination of the hazard, vulnerability, and exposure) (Seneviratne et al., 2021; Zscheischler et al., 2020). Note that even though the individual component may not be extremes themselves (or record-breaking events), the combined events with deviation from the mean state may cause cumulative and amplified extreme impacts (Hegerl et al., 2011; Leonard et al., 2014; Mitchell et al., 2014; Rummukainen, 2012; Tschumi et al., 2022b).

Droughts and hot extremes, which are among the most disastrous extremes, may occur at a wide range of time scales and their concurrences can lead to disastrous impacts. Droughts are often induced by precipitation deficits or high evaporative demand and may persist from

several months to years or decades (Dai, 2013; Hao et al., 2018e; Mishra and Singh, 2010; Vicente-Serrano et al., 2020a; Zhang et al., 2022a), while high temperature or heatwaves (usually associated with anticyclones) may last from weeks to months (Di Luca et al., 2020; Merz et al., 2020). These two extremes usually co-occur mainly due to land-atmospheric feedbacks (Seneviratne et al., 2021). Many extreme impacts of droughts and heatwaves in recent decades, such as those during summer 2003 in Europe and 2010 in Russia (as shown in Fig. 1), essentially resulted from their concurrences (or hot droughts, warm droughts) (de Ruiter et al., 2020; Geirinhas et al., 2021; Nguyen et al., 2021; Sedlmeier et al., 2018; Wu et al., 2021e; Zscheischler and Fischer, 2020). In this study, we mainly focus on the concurrent (simultaneous) occurrences of droughts and hot events at the same geographical location, which is commonly evaluated in previous studies. Unless otherwise specified, we will use the term “compound droughts and hot events or extremes” (abbreviated as CDHEs) to describe this type of compound events throughout this manuscript. Here the drought indicator and hot indicator are not necessary to be extremes.

The amplified impacts of CDHEs have spurred increasing interest in understanding these events. However, a synthesis of the recent advances and challenges in understanding and modeling CDHEs is still lacking. Therefore, there is a pressing need to review current progress in the study of CDHEs, including their characteristics, drivers, changes (observation, attribution, and projection), and impacts, thereby identifying research gaps and future opportunities. This synthesis is expected to aid the scientific and operational communities to cope with CDHEs under global warming.

2. Identification and characterization of CDHEs

2.1. Identification

Compound events can be identified as a subset of the two-dimensional probability space defined by the underlying indicators of droughts and hot extremes (X, Y), which can be correlated or not. This subset can be defined in a simple way as (X, Y) in $[0, x] \times [y, \text{infinity}]$ or by more complex functional relationships describing the adverse impact I (e.g., loss in crop yield, reduced water resources) in terms of X and Y (using precipitation and temperature as examples). In the following, we mainly introduce two approaches that have been commonly applied for

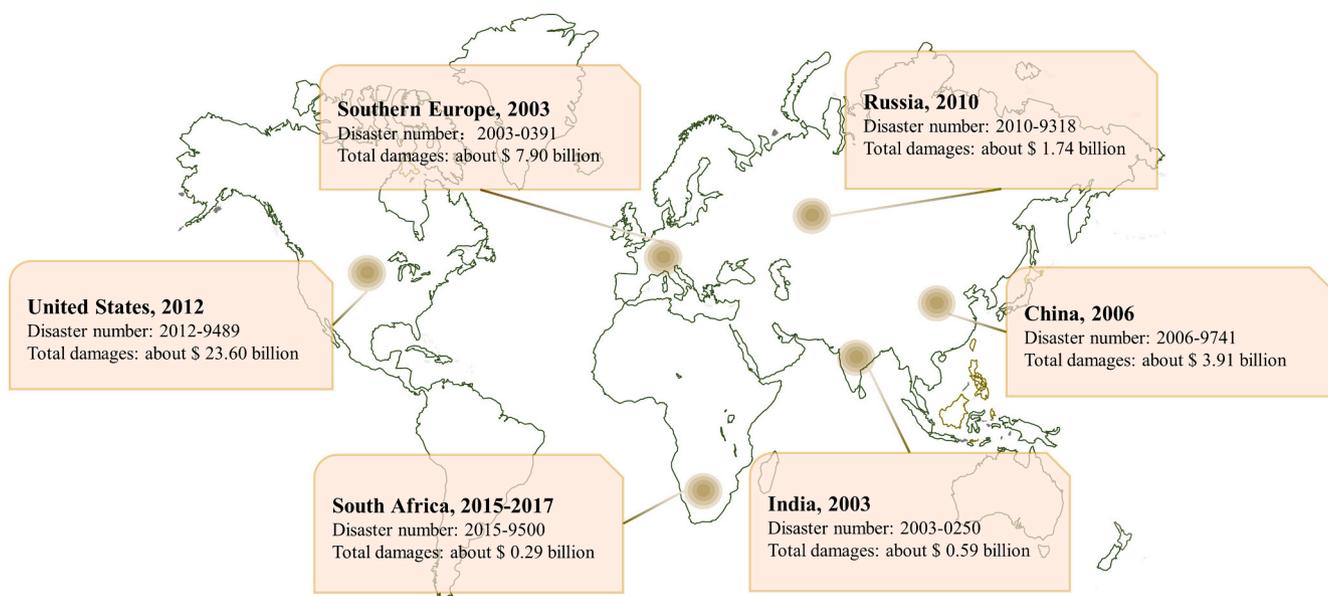


Fig. 1. Illustrations of several concurrences of droughts and hot extremes in the past few decades across the globe. These events are identified from the Emergency Events Database (EM-DAT).

identifying CDHEs in previous studies.

2.1.1. Combined thresholds approach

The intuitive identification of CDHEs is based on the concurrence of dry and hot events (e.g., concurrent low precipitation and high temperature) using selected thresholds of individual variables or indicators. Specifically, the CDHEs based on concurrences of exceedance or non-exceedance of two variables are commonly defined as a binary variable Z :

$$Z = \begin{cases} 1, & X \leq x_0 \text{ and } Y > y_0 \\ 0, & \text{others} \end{cases} \quad (1)$$

where X and Y are the indicators of dry conditions and hot conditions with thresholds x_0 and y_0 , respectively.

A variety of drought indicators (e.g., relative humidity, precipitation, soil moisture, and related indicators) and hot indicators (e.g., temperature or related indicators) of different time scales have been employed to define CDHEs. For example, a large body of drought indicators, such as precipitation, soil moisture, Standardized Precipitation Index (SPI), Palmer Drought Severity Index (PDSI), Meteorological drought Composite Index (MCI), and Standardized Precipitation Evapotranspiration Index (SPEI), have been used for defining CDHEs at the monthly/seasonal time scale, weekly time scale (Mukherjee and Mishra, 2021) or daily time scale (Mo and Lettenmaier, 2020; Tian et al., 2021; Yu and Zhai, 2020a; Yu and Zhai, 2020b). For the indicator of hot extremes, previous evaluations are commonly based on daily maximum temperature while nighttime temperature has also been employed (Feng et al., 2021b; Wang et al., 2020a; Xu and Luo, 2019). In addition, there are different ways to select the thresholds of individual indicators to define CDHEs, such as the relative values (e.g., 90th percentile of temperature, 2 standard deviations above the mean, 100-year return period) or absolute values (e.g., precipitation lower than 1 mm as dry conditions, temperature higher than 35° as hot conditions) (Barrucand et al., 2014; Beniston, 2009; Estrella and Menzel, 2013; Keller et al., 2017; Lemus-Canovas and Lopez-Bustins, 2021; Martin and Germain, 2017; McPhillips et al., 2018; Ridder et al., 2020; Tilloy et al., 2021; Vogel et al., 2021a).

The copula-based joint distribution is an alternative way to define multivariate events or extremes with multiple variables, such as precipitation and temperature, based on certain thresholds (Bevacqua et al., 2017; Flach et al., 2017; Rana et al., 2017; Schoelzel and Friederichs, 2008; Serinaldi, 2016; Singh et al., 2020; Tilloy et al., 2020). It is advantageous in constructing the multivariate distribution independently of marginal distributions and can be employed to model flexible dependence structures of multiple variables, including the extremal dependence in the tail (or tail dependence), temporal dependence, and spatial dependence, based on a wide range of copula functions, such as Frank, Clayton, Gumbel, t, or Gaussian copula (Sadegh et al., 2018; Tootoonchi et al., 2022; Zscheischler et al., 2020; Zscheischler and Seneviratne, 2017). Recently, it has been employed for modeling the dependence of compound events, including the non-stationarity modeling under a changing climate (Brunner et al., 2021b; Sarhadi et al., 2018; Singh et al., 2021).

For two random variables X and Y , the copula model can be expressed as (Nelsen, 2006):

$$P(X \leq x, Y \leq y) = C(F_X(x), F_Y(y); \theta) \quad (2)$$

where x and y are realizations of X and Y , respectively, which can be specified as certain thresholds; $F_X(x)$ and $F_Y(y)$ are the marginal probabilities of X and Y , respectively; θ is the parameter of the copula. Note that the underlying variables (X , Y) of compound events do not have to be correlated.

For example, the probability of the concurrence of low precipitation (X) and high temperature (Y) can be computed based on copula C as (Zscheischler and Seneviratne, 2017):

$$p = P(X \leq x, Y > y) = u - C(u, v) \quad (3)$$

where $u=F_X(x)$ and $v=F_Y(y)$ are marginal probabilities. The probability p in eq. (3) has been commonly employed to evaluate the likelihood of CDHEs at regional and global scales (AghaKouchak et al., 2014; Alizadeh et al., 2020; Lazoglou and Anagnostopoulou, 2019; Ribeiro et al., 2020b).

2.1.2. Indicator approach

Compound events or extremes are usually associated with adverse impacts (though not always). As such, a compound event based on indicators of droughts and high-temperature extremes (X and Y) can be defined by:

$$I(X, Y) > c \quad (4)$$

where I could be the impacts resulting from droughts and hot extremes (e.g., loss in crop yields, decreased water resources); c can be a critical threshold. This equation identifies CDHEs based on the adverse impacts of (X, Y) greater than a critical threshold c . For example, CDHEs can be defined as the subset in the X - Y space where crop yields are particularly low (resulting from droughts and hot extremes, but not from other hazards or extremes). Here the indicator of the impacts $I(X, Y)$ can be obtained from the crop model, vegetation model, hydrological model, or other impact models. The indicator approach incorporates the two extremes into one index to assess the statistical relationships between extremes and impact data (Potopová et al., 2020; Vogel et al., 2021b; Zampieri et al., 2017; Zscheischler et al., 2017). In essence, the expression of I can be any functional relationship from droughts and hot extremes (i.e., X and Y) to impacts.

In certain cases, the impact data may not be available, and some proxies (e.g., based on the joint probability or return periods) can be used to develop indicators of compound events, which turns compound event analysis into the univariate case (Hao et al., 2020b; Li et al., 2021a; Zscheischler et al., 2017). A variety of indicators have been developed to characterize CDHEs by integrating both drought and hot indicators (Abbasian et al., 2021; Hao et al., 2018d; McKinnon et al., 2021), which can be constructed by combining multiple properties or events through statistical approaches, such as linear regression model, Principal Component Analysis (PCA) or joint distribution (Gallant and Karoly, 2010; Gallant et al., 2014; Hao et al., 2020b; Zhang et al., 2020a).

2.2. Characterization

Based on the identification of CDHEs, different characteristics can be obtained accordingly. These characteristics or properties include but are not limited to the frequency, duration, timing, severity (or magnitude), and spatial extent, which are all useful to characterize CDHEs, as shown in Fig. 2. Though it is generally straightforward to define these properties of univariate extremes based on individual variables or associated indicators (Brunner et al., 2021a; Brunner et al., 2021b; Feng et al., 2020; Field et al., 2012; McPhillips et al., 2018), the characterization of CDHEs based on these properties is not straightforward due to the involvement of multiple contributing variables. In the following, we focus on several properties that have been commonly assessed in previous studies.

2.2.1. Frequency, duration, timing, severity, and spatial extent

The frequency of CDHEs can be defined by any set A within the joint X - Y space (e.g., low precipitation and high temperature), where (X , Y) in A is counted as the occurrence of a CDHE. These events can then be counted and divided by the length of the total period considered. It is among the most commonly assessed characteristics of CDHEs. For example, Fig. 3(a) shows the frequency of concurrent low precipitation and high temperature during the warm season, which is defined as

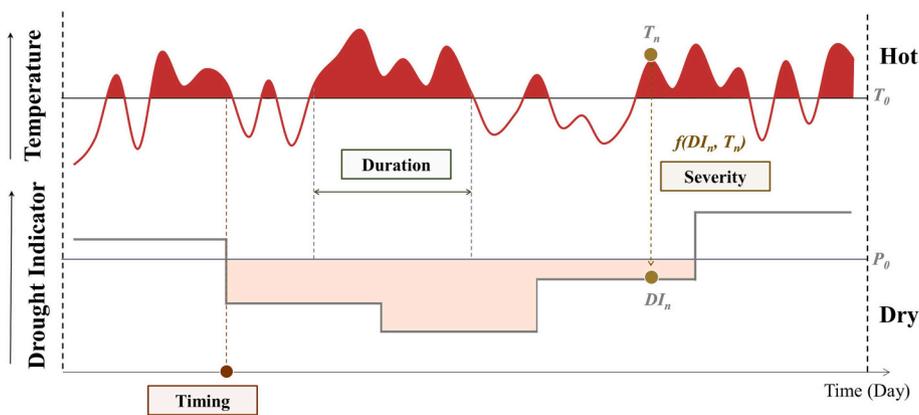


Fig. 2. Illustration of different properties of CDHEs including duration, timing, and severity based on drought indicator (DI) and temperature (T). The severity is defined as the function of properties of DI and T . P_0 and T_0 are thresholds of DI and T , respectively.

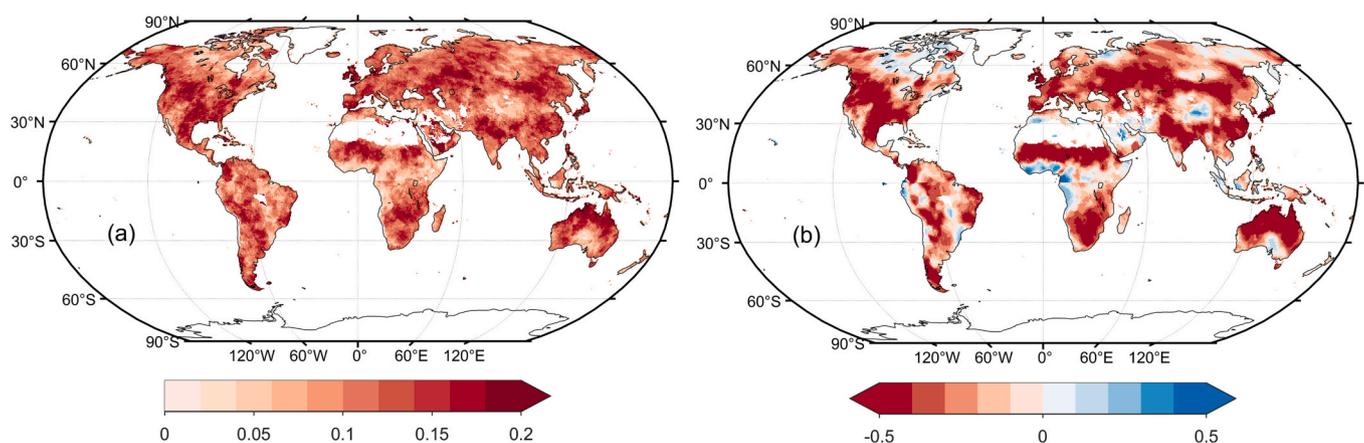


Fig. 3. Climatology frequency of CDHEs (a) and precipitation-temperature correlations (b) of the warm season (JJA for the Northern Hemisphere and DJF for the Southern Hemisphere) based on monthly precipitation and temperature data from Climatic Research Unit (CRU) for the period 1951–2018. The 30th percentile and 70th percentile of precipitation and temperature, respectively, are used as thresholds to define CDHEs.

June–July–August (JJA) in the Northern Hemisphere and December–January–February (DJF) in the Southern Hemisphere, based on Climatic Research Unit (CRU) data from 1951 to 2018. A high frequency of CDHEs is shown during warm seasons over land areas, such as central North America, Europe, and east Asia.

The duration of CDHEs is related to the frequency but with a focus on the length of consecutive occurrences (Manning et al., 2019; Mazdiyasn and AghaKouchak, 2015). A close concept to the duration is persistence, which has also been employed for the characterization of compound events (Messori et al., 2021; Pfeiderer et al., 2019). The impact of climate extremes on ecosystems is closely related to the timing (Bati-beniz et al., 2022; Flach et al., 2021; Sippel et al., 2016b), so as for CDHEs (Vogel et al., 2021a). This includes the time for the onset, succession, and recovery. For example, the onset of CDHEs can be defined as the first day with the occurrence of heatwaves during a dry period (Zhang et al., 2022c), as shown in Fig. 2.

The frequency, duration, and timing do not fully characterize a compound event. The severity level of compound extremes is also of interest (Huang et al., 2021; Manning et al., 2019; Wu et al., 2019a). For example, a compound event with precipitation of 5th percentile and temperature of 95th percentile is expected to be more severe than that with precipitation of 25th percentile and temperature of 75th percentile. The severity level of CDHEs can be characterized based on the functional relationships of the properties of dry and hot indicators (shown in Fig. 2), such as the joint probability (and its standardization) (Hao et al., 2018a; Hao et al., 2020b; Li et al., 2018a; Li et al., 2020b; Li et al.,

2021a), return period (Alizadeh et al., 2020), or product (Mukherjee and Mishra, 2021; Reddy et al., 2022). This characteristic of CDHEs is also termed “magnitude” in several studies (e.g., temperature properties during the dry periods) (Lemus-Canovas and Lopez-Bustins, 2021; Manning et al., 2019; Wu et al., 2019a). For example, a Dry-Hot Magnitude Index (DHMI) of CDHEs is developed recently by taking into account both the severity level of droughts and hot extremes, which can be expressed as (Wu et al., 2019a):

$$DHMI = \sum_{m=1}^M [P(\Delta T_m) \Delta DI_m] \quad (5)$$

where M is the number of periods (e.g., months) during which the DHMI is defined; ΔT_m is the temperature above a specific threshold for each period m ; $P(\Delta T_m)$ is the marginal distribution function of ΔT_m ; ΔDI_m is the difference between the drought indicator DI and a specified threshold for the period m with dry conditions.

The spatial extent of compound events at regional or global scales can be defined as the area coverage of the occurrence of a compound event for each period. It can also be defined as the spatial extent or area coverage of duration longer than several days or severity higher than certain values. In addition, there have been certain efforts in developing an extreme index based on the spatial extent to characterize multivariate extremes, such as the climate extreme index (CEI) (Karl et al., 1996) or their variants (Gallant and Karoly, 2010; Gleason et al., 2008) that combine the spatial extent of multiple extremes (e.g., an average of the spatial extent of different extremes, such as annual maximum

temperature, annual PDSI, the proportion of heavy-rain days in a year, number of wet/dry days in a year)(Gallant et al., 2014).

2.2.2. Dependence and joint return periods

Dependence between dry and hot indicators (e.g., correlations between precipitation and temperature) can affect the occurrence frequency of CDHEs, and thus a multivariate perspective is important for assessing changes in extremes (Zscheischler and Seneviratne, 2017). The negative precipitation and temperature correlations during the warm seasons have been extensively explored in different regions (Abatzoglou et al., 2020; Adler et al., 2008; Mahony and Cannon, 2018; Trenberth and Shea, 2005), such as the United States (Koster et al., 2009; Madden and Williams, 1978; Zhao and Khalil, 1993), Canada (Singh et al., 2021; Singh et al., 2020), Europe (Crhová and Holtanová, 2018; Lhotka and Kyselý, 2022; Rodrigo, 2015; Rodrigo, 2021), Mediterranean (Russo et al., 2019), and China (Du et al., 2013; He et al., 2015; Wu et al., 2019b), as shown in Fig. 3(b). We select the monthly precipitation and temperature data from 1901 to 2018 in southern Africa to demonstrate the dependence (with the measure of Pearson's correlation coefficient) and joint return period of CDHEs. The scatterplot of precipitation and temperature during the warm season (i.e., DJF) in southern Africa is shown in Fig. 4. The negative correlation coefficient indicates that warm-dry events tend to occur, which results from both the land-atmosphere interaction and atmosphere circulation anomalies (Feng and Hao, 2021; Lyon, 2009). The low precipitation and high temperature during DJF of 2015–2016 clearly show the concurrence of droughts and hot extremes during this period (Hao et al., 2019a; Yuan et al., 2018; Zscheischler and Lehner, 2022), which results from the influences of

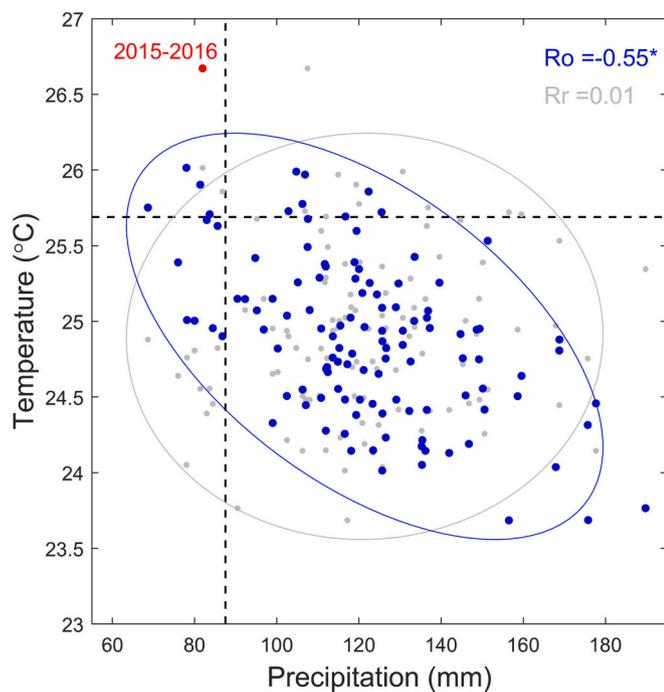


Fig. 4. Scatterplot of observed average precipitation and temperature for DJF from 1901 to 2018 in southern Africa based on monthly data from CRU (blue dots). The gray dots indicate values with randomly permuted temperature (Zscheischler and Seneviratne, 2017). The 95% confidence ellipses of the observed and permuted pairs are also drawn. The dashed lines indicate the 10th percentile of precipitation and 90th percentile of temperature. R_o and R_r are correlation coefficients of the observed and random permuted precipitation and temperature pairs. * indicates significant correlation coefficient at the 0.05 significance level. The low precipitation and high temperature during DJF of 2015–2016 are shown in the figure legend. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

multiple factors such as strong El Niño or poleward expansion of the subtropical anticyclones (or poleward expansion of the tropics) (Burlis et al., 2019; Sousa et al., 2018).

The joint return period has been used for determining the rarity (or risk) of compound extremes (including CDHEs), which is commonly achieved based on the joint probability estimated from the copula-based multivariate distribution (AghaKouchak et al., 2014; Alizadeh et al., 2020; Hao and Singh, 2020; Ridder et al., 2022a; Zscheischler and Fischer, 2020). As an example, we use the 10th and 90th percentile of precipitation and temperature, respectively, to define compound droughts and hot extremes. The Likelihood Multiplication Factor (LMF), which is defined as the likelihood of low precipitation and high temperature (either estimated from counting or parameter copula) divided by that of the independence case, is employed here to demonstrate the impact of dependence on the likelihood and return period of compound events (Zscheischler and Seneviratne, 2017). If we assume independence, the joint probability of precipitation lower than 10th percentile and temperature higher than 90th percentile is 0.01 and the joint return period would be 100 years (Singh et al., 2021). We then use copula to model the joint distribution of precipitation and temperature, in which the marginal distribution is estimated with the Gringorten plotting position formula. Five commonly used copulas (Gaussian, t, Frank, Gumbel, Clayton) were used as candidates, and the Gaussian copula was selected based on Bayesian Information Criterion (BIC) in the R package VineCopula (Nagler et al., 2022). Based on the fitted copula, the joint probability of precipitation lower than 10th percentile and temperature higher than 90th percentile is 0.035, resulting in the $LMF = 3.5$, which is higher than 1 (or higher than that based on independent assumption). In addition, the joint return period is estimated as 28 years, which is much shorter than the independent case. The difference is related to the precipitation-temperature correlations that reflects the interaction of droughts and hot extremes.

3. Physical drivers of CDHEs

Persistent dry conditions could result from slow-moving (or stationary) weather situations or recurrent large-scale circulation patterns that produce less precipitation (Hao et al., 2018e; Herrera-Estrada et al., 2019; Kingston et al., 2015; Schubert et al., 2016; Seager et al., 2015). Meanwhile, extreme heat is commonly controlled by high-pressure systems (or anticyclonic circulations) and influenced by land surface conditions (e.g., soil moisture), which is associated with subsidence of air (adiabatic compression), clear skies (high insolation), and warm air advections (Horton et al., 2016; Perkins, 2015). The interplay of multiple drivers or processes in the atmosphere, land, and ocean, as well as the background of global warming manifests in a myriad of ways in driving the concurrences of droughts and hot extremes (García-Herrera et al., 2010; Gibson et al., 2017; Miralles et al., 2019; Sousa et al., 2020; Wehrli et al., 2019). In general, CDHEs result from a variety of processes (atmospheric circulation and modes of variability, soil moisture-temperature feedback), which spans different time scales (Hao and Singh, 2020; Seneviratne et al., 2021; Zhang et al., 2021a; Zscheischler et al., 2020).

Atmosphere circulation patterns (e.g., high-pressure systems) can induce both droughts and hot extremes, contributing to the concurrence of the two extremes at shorter time scales (Fink et al., 2004; Ha et al., 2022; Miralles et al., 2019; Quesada et al., 2012; Seager and Hoerling, 2014; Zscheischler et al., 2020). Typically, high-pressure systems are often associated with descending air or reduced moist air inflow (i.e., anomalous moisture from local recycling or advection from the ocean), favoring drought conditions (Dong et al., 2018; Fischer et al., 2007; Ionita et al., 2021; Liu and Zhou, 2021; Marengo et al., 2022; Mukherjee et al., 2020; Schubert et al., 2014; Seo et al., 2021; Zampieri et al., 2009; Zscheischler and Fischer, 2020); meanwhile, they are typically associated with air subsidence (inducing adiabatic heating), increased clear-sky conditions (little cloud cover) and increased shortwave radiations,

resulting in surface warming (Berkovic and Raveh-Rubin, 2022; Chang and Wallace, 1987; Fang and Lu, 2020; Horton et al., 2016; Kornhuber et al., 2020; Kornhuber et al., 2019; Li et al., 2020d; Li et al., 2019a; Wang et al., 2019a), which collectively induce concurrences of droughts and heatwaves. Large-scale circulation patterns, such as blocking highs, planetary wave patterns, and monsoon failures, have been shown to induce CDHEs depending on regions or seasons (Zhang et al., 2021a; Zscheischler et al., 2020). In the Northern Hemisphere or midlatitude, anticyclonic circulation (embedded in large-scale atmospheric wave trains or as blockings) can induce the occurrence or persistence of CDHEs in multiple regions (Ali et al., 2021; Coumou et al., 2018; Kautz et al., 2022; Röthlisberger and Martius, 2019), including North America (Cowan et al., 2017; Dong et al., 2018), Europe (Ionita et al., 2021; Nagavciuc et al., 2022; Weiland et al., 2021), Russia (Schubert et al., 2014), and northwestern China (Luo et al., 2020). For example, in Europe, the hot and dry events during summers are generally associated with persistent high-pressure systems or atmospheric blocking circulations (i.e., steering hot and dry air northward) (Ionita et al., 2021; Kautz et al., 2022; Lansu et al., 2020; Messori et al., 2021; Weiland et al., 2021). A telling example is the 2003 Europe heatwaves accompanied by droughts, which is shown to result from blocking patterns and warm horizontal advection (and heat accumulations) in the atmospheric boundary layer, under which local drying and enhanced sensible heat fluxes further amplify hot extremes (Hu et al., 2019; Miralles et al., 2014; Sousa et al., 2020; Zampieri et al., 2009). In India, the failure of the summer monsoon and associated atmospheric conditions (increased geopotential height, weak moisture transport) is shown to contribute to CDHEs (Mahto and Mishra, 2020; Mishra et al., 2021). In the Yangtze-Huaihe River Basin (YHRB) of China (or central-eastern China), during a strong East Asia summer monsoon (EASM), the western Pacific Subtropical High (WPSH) is usually located more to the north, leading to less monsoon rainfall and favoring the occurrence of CDHEs in this region (Yao et al., 2022).

The large-scale modes of variability, such as El Niño-Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO), are closely related to the formation of high-pressure systems and favor the concurrence of low precipitation and high temperatures (or droughts and hot extremes) at longer time scales (Hao et al., 2018c; Lyon, 2009; Mukherjee et al., 2020; Wang et al., 2014; Wu et al., 2021b). Typical

modes of climate variability that lead to CDHEs include ENSO (seasonal-to-interannual time scales), Pacific Decadal Oscillation (PDO), and Atlantic Multidecadal Oscillation (AMO) (decadal and longer time scales) depending on regions and seasons (Hao et al., 2019b; Lemus-Canovas, 2022; Mukherjee et al., 2020; Wang et al., 2014; Wu et al., 2021b). ENSO has been shown to affect the seasonal occurrences of CDHEs across multiple regions (Feng and Hao, 2021; Hao et al., 2018c; Mukherjee et al., 2020), such as northern South America (Fasullo et al., 2018), southern North America (Livneh and Hoerling, 2016), southern Africa (Archer et al., 2017; Lyon, 2009), India (Bandyopadhyay et al., 2016; Mishra et al., 2020), Northeastern China (Hao et al., 2021a; Wu et al., 2021b), and Australia, as partly demonstrated in Fig. 5. Other modes of climate variability (e.g., NAO, PDO, AMO) have been shown to affect CDHEs across different regions, such as NAO for Europe or Mediterranean areas (Bladé et al., 2012; Deng et al., 2022; Ionita et al., 2017; López-Moreno et al., 2011; Li et al., 2020b; Wright et al., 2014), AMO for northeastern China (Li et al., 2020b; Wu et al., 2021b), and combined ENSO and Indian Ocean Dipole (IOD) for Australia (Lim et al., 2019; Loughran et al., 2019; Min et al., 2013; Reddy et al., 2022).

The soil moisture-temperature feedback can result in concurrent droughts and high-temperature anomalies, which are connected through the soil moisture and evapotranspiration, especially in water-limited areas (Bastos et al., 2021; Benson and Dirmeyer, 2021; Berg et al., 2016; Dirmeyer et al., 2013; Herrera-Estrada and Sheffield, 2017; Miralles et al., 2019; Osman et al., 2022; Seneviratne et al., 2012; Zscheischler and Seneviratne, 2017). Soil moisture links the water and energy cycles through the control of evaporation and affects many processes relevant to anomalies of temperature (e.g., sensible/latent heat flux exchange between atmosphere and surface, heat transport) and precipitation (e.g., local evaporation, moisture advection) (Berg et al., 2015; Freychet et al., 2021; Gevaert et al., 2018; Schumacher et al., 2022; Seneviratne et al., 2010; Zhou et al., 2019). The interaction of droughts and heatwaves causing CDHEs can be summarized as the following two processes (Miralles et al., 2019; Seneviratne et al., 2010): (1) the drying-out of soil moisture and vegetation can limit the evapotranspiration (and latent heat flux), which may also lead to precipitation deficits, and induce increased sensible heat flux and surface air temperature; (2) during heatwaves, increased evapotranspiration resulting from high vapor pressure deficit (VPD) or radiation could deplete soil

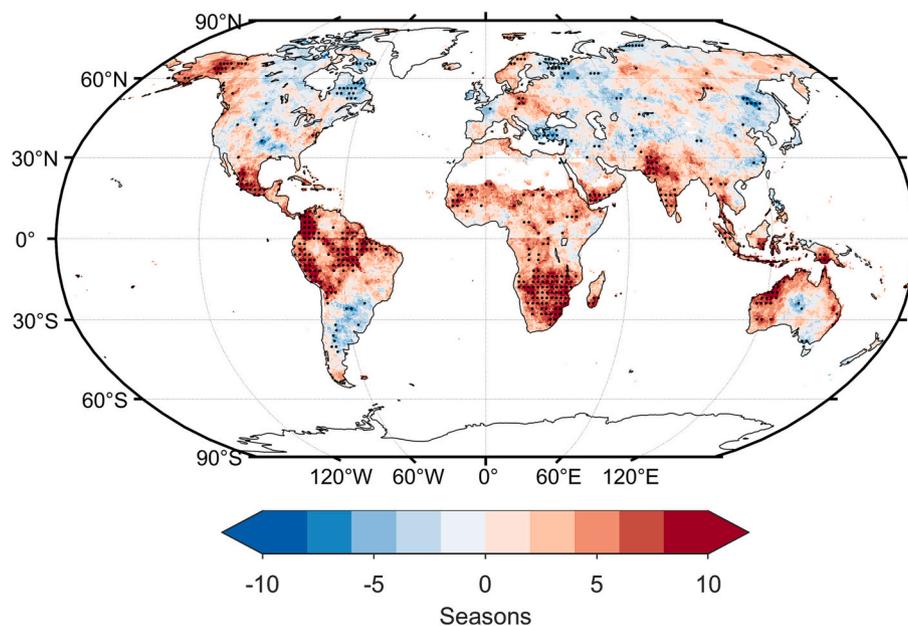


Fig. 5. Impact of ENSO on CDHEs during the warm season based on composite analysis. The monthly precipitation and temperature data are obtained from CRU for the period 1951–2018. The 30th percentile and 70th percentile of precipitation and temperature, respectively, are used as thresholds to define CDHEs. Dotted regions indicate significant impacts of ENSO on CDHEs at the 0.05 significance level based on the t-test.

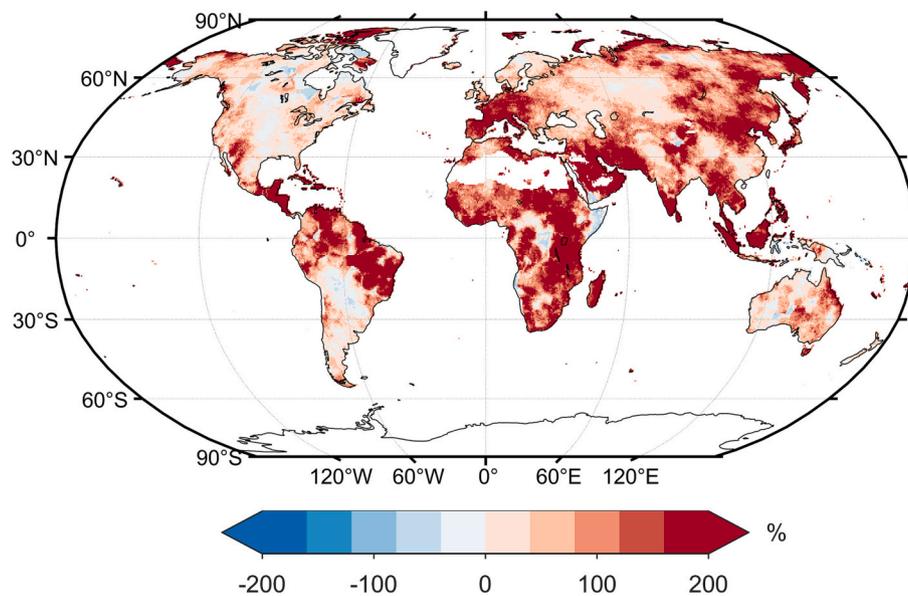


Fig. 7. Changes in the frequency of CDHEs between the two periods 1951–1984 and 1985–2018 based on monthly precipitation and temperature data from CRU. The 30th percentile and 70th percentile of precipitation and temperature, respectively, are used as thresholds to define CDHEs. Revised from Hao et al. (2013).

spatial extent of CDHEs in recent decades. An overall increase in the frequency of CDHEs (dry condition based on precipitation) in recent decades from 1960 to 2010 is observed in large parts of the United States, with regional differences (Mazdiyasni and AghaKouchak, 2015). An increase in the frequency CDHEs with dry conditions based on relative humidity from 1950 to 2019 is observed in the southwestern United States (McKinnon et al., 2021). The increased frequency of CDHEs is more profound in the past 50 years based on a long period of analysis (1896–2017) in the western United States while insignificant changes are shown in eastern regions (Alizadeh et al., 2020). The increased spatial extent is also observed in the United States as a whole for different study periods (Alizadeh et al., 2020; Mazdiyasni and AghaKouchak, 2015).

The changes in the dry-hot dependence (or correlations) can be just as important as other properties if not more so. Several lines of investigations have evaluated changes in the precipitation and

temperature correlations (or co-variability) at the global scale in observational periods (Hao et al., 2019c; Wang et al., 2021b), which is generally more heterogeneous compared with changes in other properties. These studies highlight the enhanced negative precipitation-temperature correlations over several regions, such as western North America, southwest Europe, and parts of northeast Asia (as shown in Fig. 8). At the regional scale, changed correlations between dry and hot indicators has been evaluated in China (Wu, 2014; Zhang et al., 2022b), the United States (Hao et al., 2020c), and Europe (Manning et al., 2019), which contributes to observed changes in the frequency or probability of CDHEs.

The impact of compound extremes depends not only on the hazard but also the exposure and vulnerability. The impacts from extremes or compound extremes would be particularly severe if they occurred in main agricultural regions or regions with higher population density (Vogel et al., 2019). Except for assessing changes in CDHEs from the

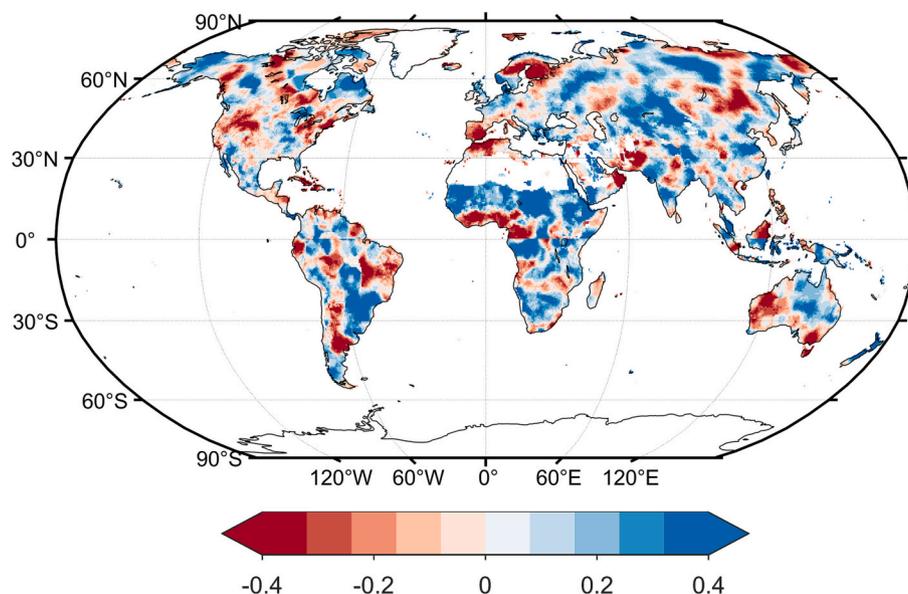


Fig. 8. Changes in the precipitation-temperature correlations of the warm season (JJA for the Northern Hemisphere and DJF for the Southern Hemisphere) for two equal periods 1951–1984 and 1985–2018 based on the CRU data. Revised from Hao et al. (2019c).

hazard perspective (e.g., frequency, severity), increased exposures of cropland to CDHEs have been observed at the global scale (Lesk and Anderson, 2021; Sarhadi et al., 2018; Wu et al., 2021c) and regional scales, including China (Feng et al., 2021b; Lu et al., 2018). Recent studies also found increased exposure of populations to CDHEs in recent decades at the global scales (Liu et al., 2021) and regional scales, including China (Wu et al., 2021d) and India (Das et al., 2022).

5. Climate model evaluation

The evaluation of global and regional climate models in simulating the mean state (i.e., climatology frequency or precipitation-temperature correlations) and historical changes of CDHEs is important to obtain necessary confidence in the modeling of chosen events or extremes, including attribution and projection analysis (Hao et al., 2013; Zscheischler and Lehner, 2022). The overall pattern of the frequency of CDHEs at a large scale can be generally reproduced by global climate models (GCMs) from the Climate Model Intercomparison Project phase 5/6 (CMIP5/CMIP6) (Wu et al., 2021c). The overall temporal increase in the frequency of CDHEs at large scales from CMIP5/CMIP6 simulations was found to be consistent with observations (Sarhadi et al., 2018; Wu et al., 2021e). At the spatial scale, the overall increase in CDHEs over large land areas can be simulated relatively well from CMIP5 or CMIP6 models; however, there are discrepancies in changing patterns or magnitude between simulations and observations, with larger bias in certain land areas, such as Australia (Hao et al., 2013; Ridder et al., 2021; Wu et al., 2021e).

The observed temperature-precipitation correlations is generally reproduced well by climate model simulations (Hao et al., 2019c; Wu et al., 2013; Zscheischler and Seneviratne, 2017). For around 75% of global land areas, the precipitation-temperature dependence from observations falls within the 10th to 90th percentile of that from CMIP5 model simulations (Zscheischler and Seneviratne, 2017). However, stronger seasonal precipitation-temperature dependence during the warm seasons across land areas has been shown in climate model simulations (Hao et al., 2019c; Rehfeld and Laepple, 2016; Wu et al., 2013), with large discrepancies in the Southern Hemisphere, which may result from model biases or observational uncertainties (Zscheischler and Seneviratne, 2017). Moreover, the observed changes in the precipitation-temperature correlations are not well reproduced by climate models (Hao et al., 2019c). The comparisons of the CMIP5 and CMIP6 in simulating CDHEs or precipitation-temperature correlations are still limited.

Regional climate models (RCMs) with high resolutions, such as those from the Coordinated Regional Climate Downscaling Experiment (CORDEX), generally captured the observed frequency of (or changes in) CDHEs in central Europe (Sedlmeier et al., 2018) and China (Lu et al., 2018). Based on simulations from CORDEX over China, RCMs were found to broadly reproduce the spatial pattern of climatology frequency of compound dry and hot days and also captured the overall increase in frequency changes (except for southwest China) (Lu et al., 2018). Other properties of CDHEs may not be captured well by RCMs. Over central Europe, the duration or temporal succession of CDHEs was not captured well, which may be due to the misrepresentation of internal variability (Sedlmeier et al., 2018). Though the direction of precipitation and temperature dependence is generally captured by RCM, the magnitude or strength of the dependence is not captured well, as shown in Canada (Singh et al., 2021) and Europe (Crhová and Holtanová, 2018; Lhotka and Kyselý, 2022) with performance depending on regions and seasons. For the simulation of precipitation-temperature correlations based on two RCMs from the EURO-CORDEX project driven by four global climate models in Europe, Crhová and Holtanová (2018) found that the simulated precipitation-temperature correlation patterns vary more across the different RCMs than GCMs (Crhová and Holtanová, 2018). These results highlight the usefulness of RCMs for assessing CDHEs; however, the assessment of whether RCMs can provide added values in simulating

the precipitation-temperature correlations or likelihoods of CDHEs is still limited.

As shown in previous sections, due to the temporal/spatial discretization and unresolved/unrepresented physical processes, system biases exist in simulations from global and regional climate models (Cannon, 2016; Sippel et al., 2016a; Van de Velde et al., 2022). Statistical bias correction methods (such as the quantile mapping method that adjusts the full distribution of variables) have been commonly used in these regional studies to correct simulations from climate models (Hao and Singh, 2020; Sedlmeier et al., 2018; Sun et al., 2019). In contrast to univariate bias correction methods with a focus on correcting a single variable, the multivariate bias correction (MBC) method is capable of correcting the dependence of multiple variables, such as precipitation and temperature (or other variables) (Cannon, 2016; Cannon, 2018; Li et al., 2014; Piani and Haerter, 2012; Vrac and Friederichs, 2015; Vrac et al., 2022). Since the impact of compound events may result from multiple variables, the bias correction of model simulations needs to consider the dependence among multiple variables (Cannon, 2018; François et al., 2020; Singh et al., 2021; Villalobos-Herrera et al., 2021; Whan et al., 2021; Zscheischler et al., 2019). Recent studies have shown that the MBC method could provide added values in improving simulations of precipitation and temperature correlations and likelihoods or properties of CDHEs in Europe (Lemus-Canovas and Lopez-Bustins, 2021), Canada (Singh et al., 2021), and China (Meng et al., 2022a). For the impact models (e.g., dynamic vegetation models, hydrological models) based on the outputs from climate models, a variety of studies have assessed the performance of different multivariate bias corrections in simulating impact variables (e.g., runoff simulations based on hydrological models) (Chen et al., 2021a; François et al., 2020; Guo et al., 2020; Meyer et al., 2019; Singh and Reza Najafi, 2020; Villalobos-Herrera et al., 2021). Albeit promising results in the MBC compared with univariate bias correction methods, several studies did not find a superior performance of the MBC, which may result from multiple factors such as the bias non-stationarity (Meng et al., 2022a; Van de Velde et al., 2022). Considering the influencing factors or potential uncertainties in the simulations from the climate and impact models, the added values of the MBC method for the compound impact analysis should be further assessed to improve the impact modeling of compound events (i.e., performance regarding the assumption, variable, and method).

6. Attribution of changes to anthropogenic climate forcing

Understanding anthropogenic influences on changes in extremes (including compound extremes) is important for climate policy and adaptation planning (Bindoff et al., 2013; NAS, 2016; Otto, 2017; Sarojini et al., 2016; Stott et al., 2016; Wang et al., 2020a). Multiple approaches have been developed for the attribution of the trend (or changes) in mean or extreme climate and specific events (i.e., event attribution) (Hulme, 2014; Sun et al., 2022; Zhai et al., 2018). The comparison between observations of current climate conditions and simulations from CMIP5/CMIP6 with different experiments (Eyring et al., 2016), including historical simulations of natural forcings (NAT) and all forcings (ALL), has been commonly used to evaluate anthropogenic influences (Chiang et al., 2021; Knutson et al., 2017; NAS, 2016; Wang et al., 2021a). The optimal fingerprinting method based on multivariate linear regression is a well-established approach for the detection and attribution of trend in climate extremes, which help answer the questions of whether climate has changed in a statistical sense and how much the changes can be attributed to causal factors with a statistical confidence (Zhai et al., 2018). For the anthropogenic influences on specific extremes (i.e., event attribution), the commonly used probability-based approach in the univariate case, including the Probability Ratio (PR) (Fischer and Knutti, 2015) and Fraction of Attributable Risk (FAR) (Stott et al., 2016), can be extended to the multivariate case for answering the questions of whether (and to what extent) anthropogenic influence has changed the likelihood or

probability of specific CDHEs (Chiang et al., 2022b; Seneviratne et al., 2021; Wu et al., 2022; Zhang et al., 2022d; Zscheischler and Lehner, 2022).

Attribution studies have revealed that the observed long-term increase in the frequency of compound events at the global scale is largely due to anthropogenic climate forcing (Chiang et al., 2022a; Chiang et al., 2022b; Sarhadi et al., 2018). For example, based on monthly precipitation and temperature observations, including data from the CRU, the University of Delaware (UDEL), and the Princeton Global Forcing (PGF), the temporal change in the annual occurrences of CDHEs across the globe based on observations and CMIP6 model simulations is shown in Fig. 9 (Zhang et al., 2022d). The consistent increase in CDHEs between observations and ALL simulations, which diverge substantially from the results of NAT simulations, indicates the dominant effect of anthropogenic forcing on the increase of CDHEs in the past century. Despite several challenges in the detection and attribution at regional scales (e.g., large magnitude of natural variability), a large number of studies have been devoted to assessing the influence of anthropogenic forcing on the long-term changes in the likelihood of CDHEs across different regions, such as China (Li et al., 2020a; Li et al., 2022c; Wu et al., 2022), the United States (Cheng et al., 2016; Diffenbaugh et al., 2015), and India (Mishra et al., 2021), which indicate human influences contribute to the long-term increase in CDHEs at regional scales. For example, based on climate model simulations of NCAR's large ensemble ("LENS"), Diffenbaugh et al. (2015) showed that anthropogenic warming increased the probability of the co-occurrence of dry-warm years (defined as precipitation anomaly lower than -0.5 SDs and positive temperature anomaly) in California. Based on the definition of indicators of CDHEs, the detection and attribution analysis of CDHEs can be conducted using the optimal fingerprinting method, as witnessed in several regions, such as northeastern China (Chen and Sun, 2017; Li et al., 2020a; Li et al., 2022c). Using the joint probability as the severity indicator of CDHEs, Li et al. (2022c) found that anthropogenic impacts on increase in CDHEs were robustly detected and anthropogenic forcings dominantly contributed to observed changes in CDHEs during 1961–2014 over northeastern China.

The evidence of human influences on specific CDHEs (or event

attribution) in historical periods has also been explored, highlighting the importance of anthropogenic influences on the increased likelihoods. Examples of the event attribution analysis include concurrent droughts and hot events based on specified thresholds (e.g., precipitation lower than 10th percentile and temperature higher than 90th percentile) (Chiang et al., 2022b; Zhang et al., 2022d) or real cases, such as those during 2019 in southwestern China (Wang et al., 2021c) and Western Cape regions (Zscheischler and Lehner, 2022). Zhang et al. (2022d) found that anthropogenic forcings caused a more than three-fold increase in the probability of CDHEs in the tropics during 1951–2010. Zscheischler and Lehner (2022) showed that anthropogenic climate change contributed at least 40% to the occurrence probability of concurrent dry and hot conditions in the years 2017 and 2019 in the Western Cape region. The impact of specific anthropogenic forcings (e.g., greenhouse gases, aerosols, land use) on CDHEs has also been evaluated (Chiang et al., 2022a; Li et al., 2022c), which can be achieved based on historical simulations from the Detection and Attribution Model Intercomparison Project (DAMIP) (Gillett et al., 2016). By comparing simulations of CDHEs in historical natural-only experiment with four alternative experiments (greenhouse gases only, aerosol only, land use-only, and all-forcing) from the DAMIP of CMIP6, Chiang et al. (2022a) found greenhouse gases alone amplified the natural frequency of CDHEs (based on 90th percentile of the joint probability of precipitation and temperature) by 1.5–5 times in tropical and extratropical regions and the aerosol effects reduced the natural frequency by 60%–100%. Many high-impact, low-probability (HILP) events or extremes related to droughts or heatwaves (e.g., 2010 Russian heatwave) have not been investigated based on the multivariate attribution framework. Overall, these attribution studies indicate the important role of anthropogenic climate change in the occurrence of historically unprecedented CDHEs in many regions across the globe.

7. Future projections of CDHEs

Climate projection of extremes under different emission scenarios provides useful insights for developing mitigation strategies and climate policy. Projections studies of CDHEs are mainly based on simulations

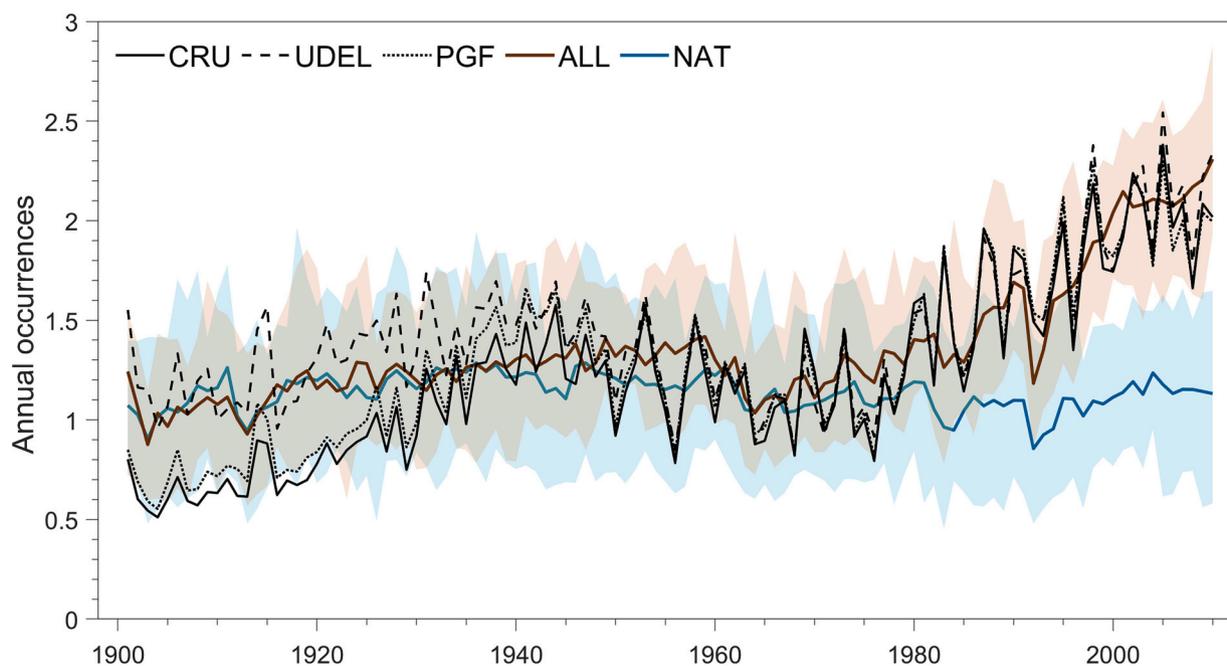


Fig. 9. Temporal change in annual occurrences of CDHEs (average number of events per year across the globe) based on observations and CMIP6 all forcings (ALL) and natural forcings (NAT) simulations for the period from 1901 to 2010. The observations of monthly precipitation and temperature data include those from CRU, the University of Delaware (UDEL), and the Princeton Global Forcing (PGF), respectively. Revised from Zhang et al. (2022d).

from climate models, such as those from the CMIP5 under different scenarios of Representative Concentration Pathways (RCPs), including the stringent mitigation scenario (RCP2.6), intermediate scenarios (RCP4.5 and RCP6.0), and the high emission scenarios (RCP8.5) (Taylor et al., 2012). More recently, projections based on the latest generation of GCMs simulations from CMIP6 have become available with RCP projections assuming certain underlying Shared Socioeconomic Pathways (SSPs) (Eyring et al., 2016). Previous projection studies suggest that the frequency of CDHEs will generally increase across the globe, which is overall consistent across different time scales, including daily (Ridder et al., 2022b; Vogel et al., 2020), monthly or seasonal (Wu et al., 2021c; Zhan et al., 2020; Zscheischler and Seneviratne, 2017), and annual time scales (Sarhadi et al., 2018). In many regions across global land areas, the frequency of extremely dry and warm seasons (based on 10th and 90th percentile of precipitation and temperature, respectively) is projected to increase by a factor of 10 between the future period in the 21st century and the historical period 1870–1969 (Zscheischler and Seneviratne, 2017). Fig. 10 shows changes in the frequency of CDHEs between the future period (2081–2100) and historical periods (1986–2005) over global land areas, indicating increased frequency in regions such as western North America, northern South America, Europe, the Mediterranean, and southern Africa (Meng et al., 2022b). In addition, the enhanced precipitation-temperature dependence is projected in large areas, such as northern extra-tropics, Amazon region, and Indonesia (Berg et al., 2015; Mahony and Cannon, 2018; Zscheischler and Seneviratne, 2017), which is associated with increased frequency of CDHEs in these areas in the future.

The Paris Agreement sets out the goal of limiting global warming to 2 °C with an inspirational goal to limit it to 1.5 °C. Multiple lines of evidence have indicated that limiting the warming to 1.5 °C will reduce the risk of droughts and heatwaves compared with that of 2 °C warming (Hoegh-Guldberg et al., 2019; Pfleiderer et al., 2019). Meanwhile, a large increase in the CDHEs can be avoided by limiting the increase of temperature to 1.5 °C rather than 2 °C in many regions across the globe. For example, over central North America and central Europe, an increase of 10% in dry-warm persistence was projected for 2 °C warming while no changes were shown for the 1.5 °C scenario (Pfleiderer et al., 2019). An even higher increase in the frequency of CDHEs was projected for the warming levels beyond the 2 °C warming (Batibeniz et al., 2022; Vogel et al., 2020). At the 3 °C warming above preindustrial levels, increased frequency of compound drought-heatwave extremes is

projected with a five-fold increase in tropical countries and an even higher increase in subtropical countries (eight-folds) and northern middle and high latitude countries (seven-folds) (Batibeniz et al., 2022).

Several regional studies also corroborated an increased frequency or probability of CDHEs at regional scales. In Africa, an increase in the frequency of CDHEs (and population exposure) is projected in simulations from regional CORDEX-CORE models, with a higher increase under RCP8.5 than RCP2.6 (Weber et al., 2020). In Asia, an increased frequency of concurrent heat waves and droughts is projected in most regions in China based on simulations from CMIP5 (Lu et al., 2018; Sun et al., 2017; Wu et al., 2021d), CMIP6 (Aihaiti et al., 2021), or other projections (Tang et al., 2022; Zhou and Liu, 2018). Simulations by CMIP5 models project a consistent pattern of increased frequency of CDHEs during summer seasons in China at global warming levels of 1.5 °C and 2 °C (under the RCP 8.5 scenario) (Wu et al., 2021d). Over India, an increased frequency of CDHEs is also projected (Das et al., 2022; Mishra et al., 2020). For example, based on CMIP6 model simulations, Das et al. (2022) projected an increase in the frequency of CDHEs across India for two future periods (2021–2060 and 2061–2100) under SSP2–4.5, SSP3–7.0, and SSP5–8.5 scenarios.

In Australia, CMIP6 models project an increase in the frequency of co-occurring heatwaves and droughts (decrease in the return periods) for 2066–2100 under SSP2–4.5 and SSP5–8.5 scenarios, especially in the south of Australia (Ridder et al., 2022a). In Europe, an increased frequency of CDHEs is projected in the future in central and southern regions, such as Germany (Estrella and Menzel, 2013). Over central Europe, the high-resolution regional climate model COSMO-CLM projected an increase in the frequency of CDHEs during summer for the future period 2021–2050 under RCP8.5, with higher changes in the Czech Republic (Sedlmeier et al., 2018). Over the Pyrenees region (transboundary areas between Andorra, France, and Spain), increased magnitude and duration in the CDHEs are projected under the RCP8.5 scenario based on the EURO-CORDEX projection (Lemus-Canovas and Lopez-Bustins, 2021).

8. Impacts of CDHEs

Both droughts and hot extremes have been shown to affect water supply, crop yield, vegetation (or carbon cycle), and wildfire risk (Bevacqua et al., 2021; Byers et al., 2018; Fink et al., 2004; Niggli et al., 2022; Ribeiro et al., 2019; Russo et al., 2017; Tschumi and Zscheischler,

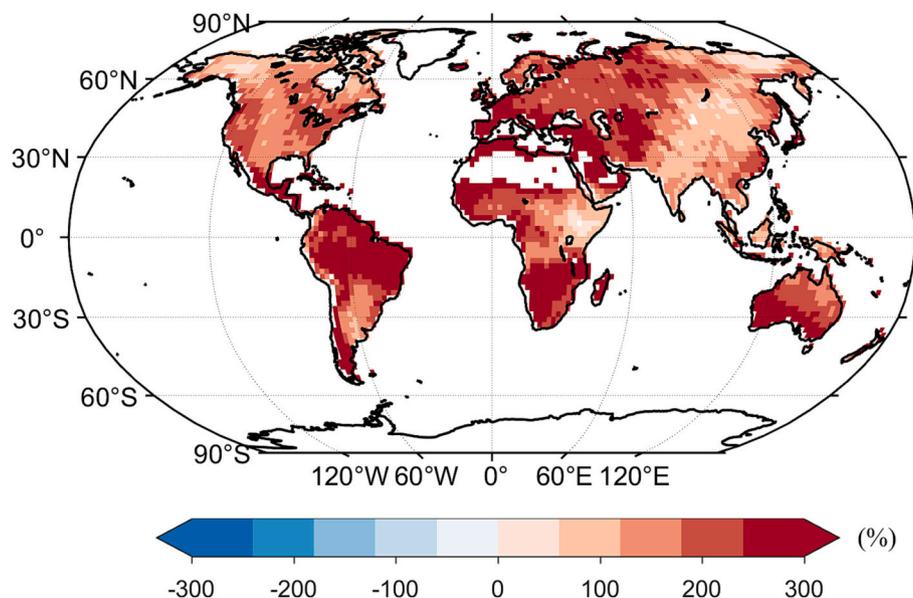


Fig. 10. Relative changes in the occurrences of CDHEs between the two periods 1986–2005 and 2081–2100 at the global scale based on monthly precipitation and temperature from CMIP6 simulations under SSP5–8.5. Revised from Meng et al. (2022b).

2019). Frequent occurrences of these extremes have spurred interest in the impact of CDHEs on natural and human systems and have gained increasing public awareness (Raymond et al., 2020a; von Buttlar et al., 2018; Zscheischler et al., 2018). In the following, we focus on the current understanding of the impact of CDHEs on water resources, crop yield, vegetation, and wildfire. We stress that there is a large body of literature on the impacts of droughts and hot extremes and we focus on those that specifically refer to CDHEs.

8.1. Water resources

Precipitation deficits (or meteorological droughts) directly cause shortages of water resources by reducing streamflow or lake/reservoir levels (i.e., hydrological droughts) (Ault, 2020). Except for precipitation deficits, the role of high-temperature anomalies (or hot extremes) in causing agricultural droughts (Ault, 2020; Dai et al., 2018; Hao et al., 2018b; Luo et al., 2017; Manning et al., 2018; Markonis et al., 2021; Weiss et al., 2009) or hydrological droughts (Brunner et al., 2021c; Udall and Overpeck, 2017; Woodhouse et al., 2016), by different processes such as atmospheric evaporative demand (AED) or snowmelt seasonality, has received increasing attention. Specifically, during summers or warm seasons, an increase in temperature leads to increased atmospheric moisture demand, reducing streamflow through increased evaporation (from open water bodies) or reduced soil moisture (e.g., increased evapotranspiration from vegetation depleting soil moisture) (Brunner et al., 2021c; Cook et al., 2014; Dai et al., 2018; Das et al., 2011; Floriancic et al., 2021; van Vliet et al., 2016). In addition, the temperature can also affect snow accumulation or snowmelt seasonality in winter, leading to hydrological droughts in the following season (e.g., warm climate in winter reduces snow accumulation resulting in a time-lagged streamflow deficit) (Brunner et al., 2021c; Bumbaco and Mote, 2010). Examples of the combined impacts of precipitation deficits and high-temperature extremes on the decrease of streamflow in recent decades have been shown in the Missouri River basin (2000–2010) and Colorado River basin (2000–2014) in the United States (Brunner et al., 2021c; Hartick et al., 2021; McCabe et al., 2017; Milly and Dunne, 2020; Udall and Overpeck, 2017). Consequently, the combined impacts of reduced streamflow (hydrological droughts) and high-temperature extremes exert pressing challenges to water planning and management due to the resulting negative impacts on irrigation, water supply, and water quantity (Martin et al., 2020), which may further affect the electricity supply or hydropower generation (Qin et al., 2020; Turner et al., 2019; van Vliet et al., 2016). Note that there are certain cases where dry and warm periods or conditions do not always lead to negative impacts. For example, in glacier regions, the increased water-melt due to warm periods can compensate for precipitation deficits (Slosson et al., 2021; Van Tiel et al., 2021).

The combined impact of the co-occurrence of precipitation deficits and warm periods has been shown to cause reduced runoff (or river flow, water resources) at annual or decadal scales (Brunner et al., 2021c; Hettiarachchi et al., 2022; Martin et al., 2020; Mastrotheodoros et al., 2020; Teuling et al., 2013; Udall and Overpeck, 2017; Van Tiel et al., 2021; Zappa and Kan, 2007). Udall and Overpeck (2017) found that, for the reduced annual flows from 2000 and 2014 in the Colorado River (associated with precipitation deficits), about one-third of flow losses were induced by unprecedented temperature. Under global warming, the role played by temperature in streamflow or hydrological droughts has increased in certain areas. Brunner et al. (2021c) showed that the spatial extent of streamflow droughts during 1981–2018 across the U.S. had increased, for which the contribution of temperature became more important over time. These impacts may further induce changes in groundwater. For example, rainfall deficits and higher evapotranspiration induced by long-lasting heatwaves could lead to the falling of groundwater levels during the recharge period, which is a pressing issue in Sweden (Chen et al., 2020). With increased temperature continuing in the coming decades, the impacts of increased compound dry and warm

years in the future may exacerbate the water scarcity in certain regions (e.g., Nile Basin), despite a projected increase in precipitation (Coffel et al., 2019).

8.2. Vegetation

Large impacts of CDHEs on the ecosystem have been reported in the summers 2003/2018/2019 in Europe and 2010 in Russia (Bastos et al., 2021; Buras et al., 2020; Ciais et al., 2005; Flach et al., 2018; Grossiord et al., 2018; Obladen et al., 2021; Tschumi et al., 2022b; Wang et al., 2020b). Droughts (or water stresses) affect vegetation photosynthesis through eco-physiological changes (e.g., reductions in stomatal conductance and enzymatic activity) or structural changes (e.g., reductions in leaf area or changes in leaf orientation) (van der Molen et al., 2011; von Buttlar et al., 2018). Temperature directly affects vegetation photosynthesis through carboxylation and electron transport (von Buttlar et al., 2018), and indirectly affect vegetation growth through increasing VPD and soil moisture deficit (Bastos et al., 2014; Wang et al., 2019c). Ample evidence has suggested amplified impacts of compound droughts and heat stresses on vegetation (e.g., growth, productivity, phenology) and carbon fluxes based on modeling, observations, and control experiments (Allen et al., 2015; Ciais et al., 2005; Dannenberg et al., 2022; Hao et al., 2020a; Li et al., 2020c; Li et al., 2021b; Mittler, 2006; Pan et al., 2020; Reichstein et al., 2007; Suzuki et al., 2014; von Buttlar et al., 2018; Zhang et al., 2021b; Zhu et al., 2017; Zscheischler et al., 2014). For example, based on the investigation of the forest response to the coincidences of low precipitation and high temperature by measuring tree ring widths (TRW) in Europe, Rammig et al. (2015) found that the percentage of years with TRW values below two standard deviations was about 6%, 9%, and 13% for those with low precipitation, high temperature, and combined dry and hot extremes, respectively.

The impacts of CDHEs on the ecosystem depend on the extreme characteristics (e.g., duration, timing) (Sippel et al., 2018; Sippel et al., 2016b; von Buttlar et al., 2018), regions (e.g., climate regimes) (Gampe et al., 2021; Hao et al., 2021a; Pan et al., 2020; Tschumi et al., 2022b), land cover types (e.g., forest and grasslands) (Flach et al., 2021; Gampe et al., 2021; Hammond et al., 2022; Hao et al., 2021a; Nicolai-Shaw et al., 2017; Tschumi et al., 2022b) and time scales (Linscheid et al., 2020), which sometimes differ due to differences in datasets (Pan et al., 2020; Stocker et al., 2019) and models (Chen et al., 2019b). von Buttlar et al. (2018) found a remarkable reduction in gross primary production (GPP) and ecosystem respiration for combined droughts and heat extremes lasting for >18 days, emphasizing the crucial role of the duration of CDHEs. Based on dynamical vegetation models, Tschumi et al. (2022b) found that the effect of changes in the frequency of extremes (including compound drought-heat extremes) was more pronounced in extra-tropics (or arid and semi-arid zones) than that in tropics (Pan et al., 2020). Considering the higher increase in CDHEs in the extra-tropics under future global warming (Batibeniz et al., 2022; Zscheischler and Seneviratne, 2017), vegetation in these regions is expected to experience a higher risk of CDHEs in the future. The impacts of climate extremes also depend on the resistance and resilience of different ecosystems (Papagiannopoulou et al., 2017). Based on in-site and satellite GPP products, Flach et al. (2021) found reduced GPP in grassland/agricultural areas under combined droughts and heat conditions, while the GPP in the forest (considered globally) was not sensitive to drought and heat events. The effect of dry-hot extremes on tropical trees is relatively small, which may be related to the maintained evaporative cooling in the tropical forests (Tschumi et al., 2022b) and trees are capable of obtaining water from deep soil layers (Mu et al., 2021; Nicolai-Shaw et al., 2017). Uncertainties exist in understanding the impact of CDHEs on vegetation due to different datasets or models. Chen et al. (2019b) assessed the drivers (including individual drivers, such as precipitation, temperature, soil moisture, and compound drivers of concurrent precipitation and temperature) of negative extreme events on GPP in China. They found that the GPP deficit driven by CDHEs was shown in most

regions of China based on the TRENDY models but only in Inner Mongolia based on the Yao-GPP model.

Though a large number of studies have shown the negative impact of CDHEs on vegetation, CDHEs do not always lead to negative impacts due to modulating effects from other factors (Flach et al., 2021; Flach et al., 2018; Li et al., 2022b; Wang et al., 2020b). Depending on the vegetation types, during dry periods (with less cloud cover or rain), the accompanying high temperature and radiation may lead to increased photosynthesis in certain regions (or precipitation indicates low solar radiation and temperature, inhibiting vegetation growth), such as Amazon rainforest (Wu et al., 2015; Zhang and Zhang, 2019). Antecedent moisture conditions may also modulate the response of vegetation to compound dry and hot extremes. During the extreme droughts and heatwaves across northern and central Europe in the summer 2018, increased carbon sink was observed in the northern areas (most ecosystems are forests), which is related to the spring legacy effect (i.e., preceding climate conditions in the response of ecosystems to summer extremes) that offset the carbon loss during summer CDHEs (Bastos et al., 2020). The elevated atmospheric CO₂ under global warming may increase terrestrial ecosystem productivity (Alan Williams, 2014). Recent analyses suggest that the effects of elevated CO₂ (and the associated increase in water use efficiency) on the physiological responses of vegetation may not alleviate the negative impacts of droughts and heatwaves (Allen et al., 2015; Birami et al., 2020; Tschumi et al., 2022b).

8.3. Crop yield

Climate variability including precipitation and/or temperature could account for about 32–39% of observed global yield variability, which varies in different regions and crops (Ray et al., 2015). Droughts and heatwaves are among the most detrimental environmental factors to crop yield or growth (Ben-Ari et al., 2018; Glotter and Elliott, 2016; Jin et al., 2017; Lesk et al., 2021; Lesk et al., 2016; Luan and Vico, 2021; Mahrookashani et al., 2017; Schauburger et al., 2021; Toreti et al., 2019; Troy et al., 2015), which has been assessed at global scales (Heinicke et al., 2022) and regional scales, including Europe (Brás et al., 2021). Based on the EM-DAT record, global droughts and heat waves have caused a reduction of nationally reported maize yields by 7% and 12%, respectively (Jägermeyr and Frieler, 2018). While sufficient water supply is expected to mitigate heat effects on crop yield (Jägermeyr and Frieler, 2018; Lobell et al., 2013; Schauburger et al., 2017; Schlenker and Roberts, 2009), the simultaneous occurrences of water stress (droughts) and heat stress can be more lethal to crops compared to a particular stress condition (Cohen et al., 2021; Goulart et al., 2021; Haqiqi et al., 2021; Lesk and Anderson, 2021; Luan et al., 2021; Mittler, 2006). The physiological impact pathway of droughts and heatwaves on crop yield differs at different stages. Droughts can inhibit photosynthesis at the vegetative stage, reduce peduncle length and slow grain development at the reproductive stage, and shorten grain-filling period at the grain filling stage, leading to a reduction of carbon uptake from photosynthesis and decreased crop yields (Kadam et al., 2014; Lesk and Anderson, 2021). The high-temperature extreme has direct and indirect effects on crop yields. The direct impacts refer to damaging photosynthetic machinery and shortening vegetative phase at the vegetative stage, decreasing rate of spikelet production at the reproductive stage, and increasing rate of leaf senescence and reducing kernel weight during the grain filling stage (Kadam et al., 2014), and the indirect impacts refer to causing stomata closure (reduction in CO₂ uptake) and enhanced root growth (reduced above-ground biomass) due to increased atmospheric water demand and depleted soil water (Lesk and Anderson, 2021; Schauburger et al., 2017; Siebert et al., 2017). Several unique physiological, molecular, and biochemical aspects exist during droughts and heat stresses (Fahad et al., 2017), including the compounding of high leaf temperature, high respiration, closed stomata, low photosynthesis, and suppressed level of proline (important for protecting plant during drought stress) (Matu et al., 2017; Mittler, 2006; Rizhsky et al.,

2002).

Different methods have been explored to quantify the relationship between CDHEs and crop yield (Hamed et al., 2021; Luan et al., 2021; Zhu and Troy, 2018). A few studies assessed the combined impact of droughts and hot extremes on crop yield based on statistical approaches (Hsiao et al., 2019; Jägermeyr and Frieler, 2018; Potopová et al., 2020), including the empirical analysis (Li et al., 2019b), regression model (Haqiqi et al., 2021; Leng, 2019; Matu et al., 2017), indicator approach (Zampieri et al., 2017), and multivariate distribution (probabilistic approach) (Feng and Hao, 2020; Hamed et al., 2021; Potopová et al., 2020; Ribeiro et al., 2020a), in which a higher impact of CDHEs on crop yields is generally found in these studies depending on seasons and crop varieties. Ribeiro et al. (2020a) quantified the impacts of dry conditions, hot conditions, and CDHEs on crop yield in Spain based on the multivariate distribution and found the probability of crop loss increased by 8 to 11% under compound dry-hot conditions compared with moderate drought conditions only. Fig. 11 demonstrates the compound dry-hot conditions induce higher probability of crop yield losses than individual dry conditions or hot conditions across top 5 maize-producing countries (Feng et al., 2019). Irrigation is an important way to mitigate the negative impacts of droughts and heatwaves on agricultural production or crop yield. Studies have shown that irrigation can lead to a decrease in compound low soil moisture and high VPD, which is expected to mitigate the potential negative impacts of CDHEs on vegetation and crops (Ambika and Mishra, 2021).

8.4. Wildfires

Wildfires can affect the carbon cycles with disastrous impacts on the composition and function of terrestrial ecosystems and the resulting air pollution, combined with heatwaves, can negatively affect human health with particular impacts on the cardiovascular and respiratory systems (Vitolo et al., 2019). Wildfires occur under three conditions, including fuel availability, fuel aridity (fire weather), and an ignition source (Ruffault et al., 2020). Low precipitation (or soil moisture deficits) can increase flammability or fuel aridity (Abatzoglou and Williams, 2016) and high temperature (or VPD) can induce accelerated plant desiccation and mortality in short periods (Allen et al., 2015; Ribeiro et al., 2022; Ruffault et al., 2020; Vitolo et al., 2019). Consequently, the concurrence of droughts and hot extremes may amplify the risk of wildfire (Crockett and Westerling, 2018; Libonati et al., 2022). A telling example is the 2019–2020 bushfires in Australia, which were shown to be a consequence of compound droughts and heatwaves (Gissing et al., 2022; Squire et al., 2021), contributing to subsequent floods, soil erosion, and reduced water quality (Kemper et al., 2021).

Droughts and hot extremes are important driving factors of wildfire activities in several regions. For example, in the Mediterranean Basin, the most extreme wildfires generally occur during periods of compound droughts and heatwaves (Ruffault et al., 2020). Studies have assessed the spatial distribution pattern of wildfires and CDHEs. Sutanto et al. (2020) explored the compound and cascading hazards defined as the concurrence of dry conditions, hot conditions, and fires at the pan-European scale. They identified a higher frequency of the concurrence of droughts, heatwaves, and fires in the west, central, and east regions of Europe. Several studies also explored the potential prediction of wildfires with multiple variables including droughts and heatwaves. For example, combined with other variables such as wind speed and relative humidity, both drought and heatwaves are shown to be important predictors for wildfire (Deb et al., 2020). Despite increased attention to the relationship between wildfires and CDHEs, more efforts are needed to bridge the gaps in the desiccation of live fuels during CDHEs to mitigate the risks of wildfires (Allen et al., 2015; Ruffault et al., 2020).

9. Discussions

Albeit recent progress in the characterization, drivers, changes, and

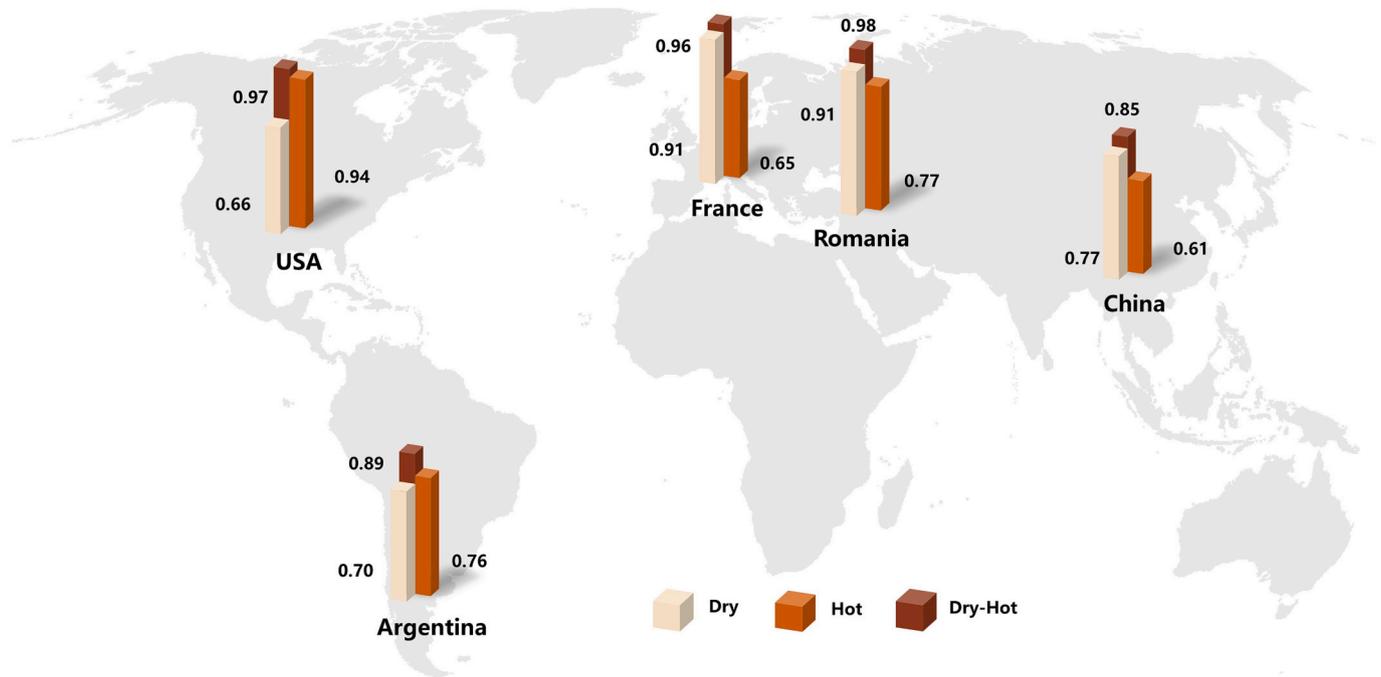


Fig. 11. The demonstration of the impact of dry conditions, hot conditions, and CDHEs on crop yield for the top five maize-producing countries based on SPI, Standardized Temperature Index (STI), and Standardized Crop yield Index (SCI). The conditional probability of crop yield loss (SCI < 0) given different conditions, including dry (SPI/STI = -1.6/0), hot (SPI/STI = 0/1.6), and dry-hot conditions (SPI/STI = -1.6/1.6) is compared. Revised from Feng et al. (2019).

impacts of CDHEs, there are still some conceptual and technical barriers in understanding and modeling of CDHEs. In the following, we discuss several challenges and future prospects for investigating CDHEs from the perspective of data, characterizations, physical mechanisms, improved evaluation and simulations, and impact assessments (as summarized in Table 1).

9.1. Data availability and quality

Data availability is an issue in extreme analysis since, without a sufficient sample size to extract large numbers of events, it is hard to identify long-term changes and perform robust statistical inferences (Seneviratne et al., 2012). Compound events or extremes are by definition less sampled than individual contributing variables (Messori et al., 2021). As such, even larger sample sizes are needed for the compound events analysis, since the characterization and modeling are usually conducted in higher dimensions (at least 2 dimensions) (Hao and Singh, 2020; Zscheischler and Lehner, 2022). For example, large sample sizes are generally needed to characterize droughts and high-temperature extremes to place them into a long-term context for return period analysis or risk assessments. However, the length of many data products are not sufficiently long, which may lead to large uncertainty in the analysis of compound events (e.g., change detection and attribution) (Hao and Singh, 2020). Moreover, analogues of a certain combination of extremes may be limited or even not exist in historical records (Gruber et al., 2021; Yiou and Jézéquel, 2020; Zscheischler et al., 2018), which hinders accurate estimation of the probability or risk of CDHEs, especially for those with low-probability and high-impacts. Data with finer resolutions are also important to characterize CDHEs across multiple time scales. For example, for heatwave-related extremes, the analysis is generally based on the weather or daily time scale (Seneviratne et al., 2021; Wang et al., 2020a), which is also needed for investigating CDHEs. Currently, the availability of high-quality daily data is limited in large regions around the world, including parts of Africa, South America, and Asia, which hampers the investigation of extremes (Sillmann et al., 2017; Yin et al., 2014).

The long-term and high-quality data are existing challenges faced in

Table 1

Advances, challenges, and future directions in studying compound dry and hot events.

Topic	Advances	Challenges	Future directions
Data	Assessment with multi-source data (e.g., gauge observations, reanalysis, and remote sensing)	Lack of long-term and high-quality data	Generate or assimilate data from multiple sources
Characteristics	Based on multiple properties, such as frequency, duration, severity, and timing	Lack of consensus on choices of indicators and thresholds	Indicator and threshold selection based on impacts
Drivers	Driven by atmospheric circulation (modes of variability) and land-atmosphere feedbacks	Complex relationships between driving factors and CDHEs at different temporal and spatial scales	Integrated analysis of process chains at multiple spatial-temporal scales
Changes	Detected, attributed, and projected increase in CDHEs across large regions	(1) Limited model evaluation in simulating CDHEs; (2) Immature representation of key processes affecting attribution and projection	(1) Develop metrics for evaluating compound events; (2) Performance-based model selection in attribution and projection studies; (3) Improve resolutions and parameterizations
Impacts	Quantify impacts on water resources, vegetation, crop yield, and wildfires	Lack of understanding of individual extremes or their interactions causing impacts	Disentangle relative effects of individual and compound extremes

the assessment and modeling of compound events from multiple lines of evidence. Different approaches (e.g., process-based model simulations, reanalysis data, and large model ensembles) have been employed to overcome this problem (Batibeniz et al., 2022). For example, large climate model ensemble simulations, such as the single model initial-condition large ensemble (SMILE) (Deser et al., 2020), have been employed to assess changes in the statistics of weather and climate extremes (including compound events) and their impacts (Bevacqua et al., 2022; Lehner et al., 2020; Raymond et al., 2022; Sippel et al., 2016a; Tschumi et al., 2022b), which can cope with the challenge of limited datasets for model evaluation and attribution (Zscheischler and Lehner, 2022). Note that different data sources may lead to differences in changes detection in droughts or hot extremes (Hoffmann et al., 2020; Mukherjee and Mishra, 2022) and attribution analysis (Zhang et al., 2022d), highlighting the importance of change assessments with different data sources. Besides the impact data in the EM-DAT database, the simulations from hydrologic models, crop models, and dynamic vegetation models can be used to address the challenge of the lack of long-term impact data. Overall, generating (i.e., model simulations, expanding observation networks, or reconstruction), pooling, or assimilating data of multiple sources (e.g., remote sensing) is needed to increase the data length and accuracy to improve the modeling of compound events and their impacts (Brunet and Jones, 2011; Hao et al., 2018d; Sillmann et al., 2017; Xia et al., 2019; Zscheischler and Lehner, 2022).

9.2. Characterizations from different perspectives

The suitable choices of variables/indicators and thresholds are challenges in characterizing and evaluating changes in CDHEs. There is still ambiguity in the definition of droughts, which hinders the characterization of CDHEs (Geirinhas et al., 2021). Most of the current analysis of concurrent droughts and high-temperature extremes is based on meteorological droughts (e.g., precipitation-related). Some sensitivities in drought changes resulting from the choice of different drought indicators have been shown in previous studies (Dai, 2013; Long et al., 2018; Sheffield et al., 2012), which makes the evaluation of CDHEs even more complicated. For example, for the frequency of compound meteorological droughts and hot extremes, the relative humidity (Yao et al., 2022), precipitation deficit/anomaly (Hao et al., 2013; Zhou and Liu, 2018), SPI (Geirinhas et al., 2021; Vogel et al., 2021a), and SPEI (Li et al., 2018b; Vogel et al., 2021a) have been employed. The impact of CDHEs may be placed on a variety of sectors, such as water supply, agriculture management, and human society. As such, CDHEs can be evaluated throughout the hydrological cycle by considering a wide range of indicators of different drought types (e.g., agricultural and ecological droughts, hydrological droughts) based on the impact concerned (Feng et al., 2022). For example, soil moisture can be used as a drought indicator to define CDHEs if the crop production or yield is of particular interest (Hamed et al., 2021; Hao et al., 2018b; Lesk and Anderson, 2021; Muthuvel and Mahesha, 2021; Sharma and Mujumdar, 2022; Zhang et al., 2019). In addition, though different combinations of thresholds have been employed for characterizing CDHEs, there is not a consensus on the selection of thresholds to define compound events. Previous studies also found certain sensitivities of changes in CDHEs due to selected thresholds of each variable (absolute or relative thresholds) or baseline periods to define the threshold (Feng et al., 2021a; Kirono et al., 2017; Sedlmeier et al., 2018). In addition to the definition of compound events from the statistical perspective (e.g., percentile-based thresholds of hydroclimatic variables), it is critical to select the indicator or thresholds in terms of impacts, which can be achieved based on impacts models (e.g., crop models, vegetation models, hydrological models) or observational data (e.g., EM-DAT). These results imply that it is important to study CDHEs from a multivariate approach in the hydrological cycle and define compound events from an impact perspective.

9.3. Understanding mechanisms of combined physical processes

Apart from analogous challenges in understanding individual droughts and hot extremes, gaps still exist in the understanding of the underlying physical mechanisms of compound extremes (Geirinhas et al., 2021; Sillmann et al., 2017). The analysis of underlying mechanisms in previous studies is mostly focused on individual extremes while the processes or drivers leading to the concurrent or consecutive occurrences of both extremes are rather limited. For example, the summer weather anomalies (e.g., hot-dry or cold-wet) in Europe are closely associated with jet stream (either dominance of blocked flow or persistence of zonal jet); however, gaps still exist in our understanding of the dynamics of underlying jet-stream variability during summer seasons (a critical period of agricultural production) (Messori et al., 2021). The causing mechanism of CDHEs can differ at different time scales. At shorter time scales, CDHEs can result from the blocking of anticyclones and soil moisture–temperature feedbacks, while at seasonal or longer time scales, the mode of variability plays important roles in driving CDHEs (Kautz et al., 2022; Miralles et al., 2019; Röthlisberger et al., 2019; Zscheischler et al., 2020). In addition, the simultaneous occurrence of CDHEs across multiple regions (connected with economical activities or exporting countries of crop yields) can affect food security and deserves future investigations (Feng et al., 2021a; Raymond et al., 2022; Sarhadi et al., 2018). As such, the dynamical relationship between multiple driving factors and CDHEs at different time scales and spatial locations can be complex, posing challenges to the understanding of CDHEs. An integrated analysis of multiple components or process chains regarding the concurrent or consecutive droughts and high-temperature extremes across different temporal-spatial scales is needed, which relies both on the high quality and long-record observations (e.g., capturing historical events) and improved modeling strategies (e.g., representing blocking systems) (Kautz et al., 2022).

9.4. Improved model evaluation and simulations

Droughts and heatwaves are connected and propagated through a variety of physical mechanisms, including synoptic processes, land-atmosphere feedback, and recurring large-scale patterns. Good performance in simulating CDHEs necessitates the models to capture individual droughts, hot extremes (or heatwaves), and their interactions or dependence during the onset, development, and recovery of CDHEs (Hao et al., 2019c; Ridder et al., 2021). However, current studies on the evaluation of climate models in simulating compound events, including CDHEs, are still limited (Hao, 2022; Ridder et al., 2021; Villalobos-Herrera et al., 2021; Zscheischler et al., 2020), which hinders the understanding of model performances. This necessitates not only the evaluation of model performances in simulating both extremes but also compound events (or the interaction of multiple contributing variables) (Zscheischler and Lehner, 2022) and the relationship between driving factors and CDHEs as well (Manning et al., 2022; Röthlisberger and Martius, 2019). To this end, novel metrics to evaluate the ability of climate models in simulating compound events are needed (Messori et al., 2021; Zscheischler et al., 2021). Building on the climate model evaluation, the model selections based on performance or process-based analysis can aid the attribution or future projections of extremes (Fischer et al., 2021; Manning et al., 2022; Vogel et al., 2018), including CDHEs.

In addition, the current capacity to simulate key processes (both regional processes and remote climate drivers or variability), such as atmospheric blocking, jet stream position and intensity, land-atmosphere interactions, and teleconnections, remains a major challenge. Regional changes in large-scale circulation features, such as changes in blocking frequency or warm horizontal advection would lead to changes in hot extremes; however, underestimation of blocking frequency exists for current climate models (Gibson et al., 2017; Scaife et al., 2010). In addition, the representation of the impacts of the land surface on precipitation and temperature extremes (or land atmosphere

feedbacks) in climate models is still immature (Miralles et al., 2019; Santanello et al., 2018; Seneviratne et al., 2021; Sillmann et al., 2017). For example, previous studies have shown that land surface models tend to underestimate the latent heat flux during droughts, which leads to an overestimation of the heat extremes by land-atmosphere feedbacks in coupled models (especially in humid regions) (Sippel et al., 2017; Ukkola et al., 2016; Ukkola et al., 2018), implying large uncertainties in CDHEs characterizations from GCMs. The deficiencies in simulating key processes may lead to difficulties or uncertainties in understanding and modeling (e.g., attributing and projecting changes) of CDHEs (Bevacqua et al., 2022). For example, the uncertainty of precipitation changes attribution is shown to result from the limited model simulations (and observations) with impacts of large internal variability (Zhai et al., 2018), which add difficulties in the attribution CDHEs with high confidence. Overall, the large bias of climate models in simulating these processes calls for theories/models to untangle complicated processes, increased model resolutions, and novel approaches for the parameterization of sub-grid scale (or fine-scale) processes (Bouwer et al., 2022; Coumou et al., 2018; Diffenbaugh et al., 2005; Meehl et al., 2021; Mueller and Seneviratne, 2014; Sillmann et al., 2017; Woollings et al., 2018). For example, the plant physiology and response to the CO₂ effect are important to be included in earth system models to capture land-atmosphere feedbacks and associated climate extremes including droughts and heatwaves (Anderegg et al., 2019; Lemordant et al., 2016; Miralles et al., 2019; Vicente-Serrano et al., 2022). Moreover, the interaction of human activities (e.g., irrigation, land use changes) with CDHEs also calls for improved modeling of related natural processes and human activities in the Anthropocene (Hao, 2022; Zscheischler et al., 2018).

9.5. Impact assessments

The modeling of the impact of CDHEs relies on both accurate climate modeling and impact modeling. The definition of CDHEs could be done from an impact perspective by asking: what are the weather/climate conditions leading to extreme impacts? To model the complicated relationship between the physical environmental (including but not limited to droughts and hot extremes) and biophysical impacts (e.g., crop failure, extremely low flow events, wildfires), an integrated climate and impact modeling is desired in defining dry-hot events of high impacts (e.g., subsets of the P-T space with extreme impacts) (van der Wiel et al., 2020). Though higher impacts of CDHEs on different sectors have been highlighted and quantified, the role of individual extremes and their interactions causing impacts is largely unquantified. As such, disentanglement of the relative effect of individual/compound extremes leading to the impacts needs more effort (e.g., how droughts regulate the impact of temperature or vice versa) (Basso and Ritchie, 2014; Tschumi et al., 2022b). Building on previous studies of impact modeling based on climate simulations and impact models, the negative impacts result from different combinations of contributing variables can be quantified from statistical methods, process-based impacts models, and socio-physical approaches (Raymond et al., 2020a). Statistical methods (e.g., conditional distribution, machine learning, or overlap in occurrences) hinge on the empirical relationship between contributing variables and the impact variable, which may fall short in characterizing the physical processes causing impacts on different sectors (Brunner et al., 2021c; Feng and Hao, 2020; Feng et al., 2019; Li et al., 2022a; Ribeiro et al., 2020a; Zhu et al., 2021). Process-based impacts models are established tools to estimate the impacts of changes in weather conditions on crop yields, vegetation, surface runoff, or river discharge, which can be employed to identify the critical hot-dry conditions leading to extreme impacts. For example, Tschumi et al. (2022b) employed the dynamic global vegetation model from a large ensemble climate modeling experiment (Tschumi et al., 2022a) to disentangle the relative importance of extremes (e.g., dry, hot, and hot-dry) on vegetation composition and carbon dynamics. The storyline approach, which starts from a given

impact and constructs a chain of events from the high impact to the driving factors (Pfleiderer et al., 2021; Shepherd et al., 2018; Sillmann et al., 2021; Zscheischler et al., 2018), can also be explored to disentangle the driving component (Goulart et al., 2021). This approach is useful in investigating the event in the tail distribution with the most catastrophic impacts (the probability may not be quantifiable in this case) (de Brito, 2021; Zscheischler et al., 2018).

10. Conclusions

Compound droughts and hot events or extremes (CDHEs) have become an area of active research in recent decades due to their severe ramifications for hydrology, ecology, and natural resources management. These compound events have been characterized based on different properties (e.g., frequency, duration, severity, timing, spatial extent, and dependence) at different time scales. Multiple physical processes, including atmospheric circulations, modes of variability (or teleconnection patterns), and soil moisture-temperature feedback, are important driving factors of the occurrences of CDHEs depending on regions and seasons. Observations-based studies reveal an overall increase in the frequency and intensity of CDHEs across the globe (e.g., western and southern North America, northern South America, Europe, Africa, northern parts of eastern Asia, and northeastern Australia), which mainly results from the increased hot extremes. Climate model simulations from CMIP5/CMIP6 generally perform well in simulating the climatology frequency of CDHEs; however, large discrepancies in changing patterns of CDHEs in historical periods between simulations and observations are observed in certain regions (e.g., Australia). Multivariate bias correction (MBC) of climate model outputs is an useful approach to alleviate potential uncertainty or bias in model simulations of CDHEs. The overall increase of CDHEs at the global or continental scales can be attributed to anthropogenic forcings, which also contributes to increased likelihoods of certain specific events or extremes. In the future, increased CDHEs are projected over most global land areas, with higher increase in the western/southern North America, northern South America (e.g., the Amazon and Brazil), central/southern Europe, the Mediterranean region, and southern Africa. Impacts from CDHEs on different sectors, including water resources, crop yield, vegetation, and wildfires, have been quantified, which highlights the larger impacts of compound extremes than their individual counterparts.

A few challenges exist in the data availability, characterization, mechanism, changes, and impacts of CDHEs. A long-term dataset with finer resolutions is needed to fully characterize CDHEs at different time scales, which necessitates generating and assimilating data from multiple sources (e.g., process-based model simulations, and reanalysis data). A consensus on the variables and thresholds to define CDHEs does not exist, which may lead to large uncertainties in the variability assessments of CDHEs. Selecting extreme indicators or thresholds based on impact data from model simulations (e.g., crop models, vegetation models, hydrological models) or observations (e.g., EM-DAT) is a promising and alternative approach. The dynamical relationship between multiple driving factors and CDHEs at different time scales and spatial locations can be complex and thus integrated analysis of multiple components or process chains with respect to droughts and hot extremes is needed to improve the physical understanding. The assessment of how climate models simulate CDHEs is rather limited, which calls for novel metrics for the model evaluation. In addition, deficiencies in simulating key processes of CDHEs still exist in climate models. Increased model resolutions and novel parameterizations of sub-grid scale are useful endeavors for future research in simulating CDHEs in the Anthropocene. Building on improved model dynamics and resolutions, modeling complicated climate-impact interactions and disentangling the contribution of driving components is useful for impact assessments and developing mitigation measures for CDHEs.

There are some limitations in this study. We focus on the concurrent droughts and hot events, while the occurrence of the two extremes at

consecutive periods (temporal compounding) or at multiple locations (spatial compounding) (Feng et al., 2021a; Raymond et al., 2022; Sarahadi et al., 2018; Slater et al., 2021; Zscheischler et al., 2020) is not considered in this study. In addition, we mainly characterize CDHEs in the bivariate case with a focus on precipitation and temperature, while the inclusion of other variables, such as VPD, soil moisture, radiation, and wind speed, to assess CDHEs may also be needed (Hao et al., 2018b; Manning et al., 2018; Noguera et al., 2022; Qing et al., 2022; Tavakol et al., 2020a; Tavakol et al., 2020b). Nevertheless, this study bears potential for investigating other types of compound events with serious repercussions on agriculture, energy demand, ecosystem, and human health (Raymond et al., 2020a; Zscheischler et al., 2020). For example, several types of compound events are also related to droughts or hot extremes, such as compound low soil moisture-high VPD (Ambika and Mishra, 2021; Zhou et al., 2019), compound droughts-floods (He and Sheffield, 2020; Visser-Quinn et al., 2019), compound heatwaves-floods (Chen et al., 2021b; Wang et al., 2019b), compound heatwaves-tropical cyclones (Matthews et al., 2019), compound warm-wet events (Brouillet and Joussaume, 2019; Findell et al., 2017; Raymond et al., 2020b; Rogers et al., 2021; Tencer et al., 2016), compound high temperature-ozone pollution (Otero et al., 2022), and compound drought-river flow temperature (Liu et al., 2018; van Vliet et al., 2016). Results from this study may provide useful insights for investigating these compound events or extremes.

Building on the synthesis in this study, a scientific consensus is emerging that the frequency and intensity of CDHEs have been increasing and may continue in the future. These results highlight the emergence of the development of buffering strategies for CDHEs (Overpeck, 2013), such as irrigation, forestation, or urban infrastructures (Ambika and Mishra, 2021; Hao, 2022; Seneviratne et al., 2021; Thiery et al., 2020; Wouters et al., 2022). It is therefore paramount to limit greenhouse gas emissions to reduce the risk of CDHEs under global warming. This study is expected to be useful for research and operational communities of a variety of sectors, including climate, forest, agriculture, and human health, to improve the resilience to cope with compound extremes under global warming.

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 to data in the manuscript.

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