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

Zengchao Hao[1], Fanghua Hao[1], Youlong Xia[2], Sifeng Feng[1], Cheng Sun[3], Xuan Zhang[1], Yongshuo Fu[1], Ying Hao[1], Yu Zhang[1], Yu Meng[1]

[1]College of Water Sciences, Beijing Normal University, Beijing, 100875, China

[2]I. M. Systems Group at Environmental Modeling Center (EMC), National Centers for Environmental Prediction (NCEP), College Park, MD 20741, USA

[3] State Key Laboratory of Earth Surface Processes and Resource Ecology and College of Global Change and Earth System Science, Beijing Normal University, Beijing, 100875, China

Corresponding Author: Zengchao Hao

Address: No. 19, XinJieKouWai St., HaiDian District, Beijing 100875, China

Email: haozc@bnu.edu.cn

Submit to **Earth-Science Review**

Abstract

Compound droughts and hot events or extremes (CDHEs) may lead to larger repercussions than do individual dry or hot extremes. Due to the disastrous impacts and increased risk of these events under global warming, increased attention has been paid to these events from both research and operational communities. This review provides a synthesis of the literature on characteristics, physical mechanisms, changes (detection, attribution, and projection), and the impact of CDHEs. Different characteristics of these events (e.g., frequency, duration, and spatial extent) are first introduced based on dry 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 influence 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.

Keywords: compound event; drought; dry and hot; extreme; climate change

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; 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 instead) (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 anomalies or 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 2010 (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 extremes or events” (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 droughts and hot extremes indicators (X,Y), which can be correlated or not. This subset can be defined in a simple way as (X,Y) in [0, x] × [y, infinity] or by more complex functional relationships describing the adverse impact I (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 the two approaches that have been commonly applied for 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:

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

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

A variety of dry 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), 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, 100-year return period) or absolute values (e.g., precipitation lower than 1mm as dry conditions, a temperature higher than 35 degrees as hot conditions) (Barrucand et al., 2014; Beniston, 2009; Estrella and Menzel, 2013; Fortin and Hétu, 2014; 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 among 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):

$$P(X \leq x, Y \leq y) = C(Fx(X), Fy(Y);\ \ \theta) \qquad (2)$$

where x and y are realizations of X and Y, respectively, which can be specified as certain thresholds; $Fx(X)$ and $Fy(Y)$ 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):

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

where $u = Fx(X)$ and $v = Fy(Y)$ are marginal probabilities. The probability p in equation (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:

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

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, the 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 droughts 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, 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 temperature during the warm season, which is defined as 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 southeast Asia.

The duration of CDHEs is related to the frequency but with a focus on the length of consecutive occurrences (Manning et al., 2019; Mazdiyasni 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; Pfleiderer et al., 2019). The impact of climate extremes on ecosystems is closely related to the timing (Batibeniz et al., 2022; Flach et al., 2021; Sippel et al., 2016b), so as for the 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 indicate how severe a compound event is. 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):

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

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 severity higher than a threshold, 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 multiple factors such as strong El Niño or poleward expansion of the subtropical anticyclones (or poleward expansion of the tropics) (Burls 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 joint exceedance of precipitation and 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 independency, 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 insolations), 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, such as stationary anticyclones, soil moisture-atmosphere interactions, and large-scale mode of variability, 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), inhibiting moisture divergence and 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 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 collectedly 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) that reduce zonal flows and divert storm tracks (southward) (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 (Yao et al., 2022).

The large-scale modes of variability, such as El Niño-Southern Oscillation (ENSO), are closely related to the formation of high-pressure systems or blocking highs 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 those associated with 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), Northeast China (Hao et al., 2021b; Wu et al., 2021b), Australia, as partly demonstrated in Fig. 5. Other modes of climate variability (e.g., NAO, PDO, AMO) have been shown to affect CDHEs depending on regions, such as NAO for the 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 evaporation (or surface temperature), 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., heat transport, solar radiation, and sensible/latent heat flux exchange between atmosphere and surface) and precipitation (e.g., local soil moisture deficits promoting rainfall deficits) (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 deficit, and induce increased sensible heat flux and surface temperature; (2) during heatwaves, increased evapotranspiration resulting from high vapor pressure deficit (VPD) or radiation could deplete soil moisture, inducing the soil moisture deficits or dry conditions, as demonstrated in Fig. 6. During this self-amplifying process, temperature extremes can both be the driver and response of droughts (Kiem et al., 2016; Lockart et al., 2009; Miralles et al., 2019; Nicholls, 2004). At the global scale, the land-atmosphere coupling between droughts and surface temperature extremes have been explored from both observations and model simulations (Berg et al., 2016; Gevaert et al., 2018; Miralles et al., 2012; Seneviratne et al., 2010; Zscheischler and Seneviratne, 2017). Evidence has shown the important role of soil moisture-temperature feedbacks in the concurrences of drought and hot extremes, such as those in the United States (Benson and Dirmeyer, 2021; Su and Dickinson, 2017), Europe (Dirmeyer et al., 2021; Hirschi et al., 2011; Ionita et al., 2021; Liu et al., 2020; Manning et al., 2018; Sousa et al., 2020; Wang et al., 2022; Whan et al., 2015; Xu et al., 2021), Brazil (Geirinhas et al., 2021; Geirinhas et al., 2022; Libonati et al., 2022), and Asia (Seo et al., 2021; Shi et al., 2021; Zhang et al., 2020b). Morever, drought conditions in the upwind can lead to the advection of enhanced sensible heat (or warmed air mass) downwind, where the land-atmosphere feedback in nearby regions is stimulated and subsequently causes or enhances heatwaves (i.e., propagations from upwind droughts to downwind heatwaves)(Miralles et al., 2019;

Miralles et al., 2014; Schumacher et al., 2022; Schumacher et al., 2019; Sousa et al., 2020; Zhou and Yuan, 2022), which can contribute to the occurrence of CDHEs in downwind regions.

4 Observed changes of CDHEs

On the global scale, multiple lines of evidence indicate a robust increase in the frequency of CDHEs defined in multiple time scales, which mainly result from the increase in high-temperature extremes (Batibeniz et al., 2022; Hao et al., 2013; Mukherjee et al., 2022; Raymond et al., 2022; Sarhadi et al., 2018; Wu et al., 2021e; Zhang et al., 2022d). Fig. 7 shows an increase in the annual frequency of CDHEs across global land areas, including western and southern North America, northern South America (e.g., Amazon), Europe, central and southern Africa, northern parts of eastern Asia, southeast Asia, and northeastern Australia, which is consistent with previous studies (Chiang et al., 2022b; Hao et al., 2013; Wang et al., 2021b; Wu et al., 2021e). Increased severity/spatial extent and lengthened duration of CDHEs are observed at the global scale as a whole, though there are regional variations (Feng et al., 2020; Hao et al., 2018a; He et al., 2022a; He et al., 2022b; Lesk and Anderson, 2021; Mukherjee and Mishra, 2021; Wu et al., 2021a; Zhang et al., 2022d). Several studies provide a systematic analysis of changes in multiple characteristics (frequency, severity, duration, and magnitude) of CDHEs (Feng et al., 2020; Mukherjee and Mishra, 2021), which found a higher frequency, long duration, higher severity level, and larger spatial extent in large regions across the globe. At the continental or regional scale, assessments of frequency changes of CDHEs point to an overall increase in CDHEs across most regions. Following Seneviratne et al. (2021), these assessments are summarized below.

In Asia, an increase in the frequency, duration, and spatial extent of CDHEs is observed in recent decades. The frequency of CDHEs presents an overall increase in East Asia or China (Chen et al., 2019a; Feng et al., 2021b; Hao, 2022; Kong et al., 2020; Seo et al., 2021; Wu et al., 2019b; Yu and Zhai, 2020b). In China, the overall increase in the frequency of CDHEs is generally consistent based on different indicators of droughts (such as SPI, SPEI, or PDSI), though some discrepancies do exist in certain regions (Chen et al., 2019a; Zhang et al., 2022c). Lengthened duration, higher severity levels (or magnitude), and increased spatial extent of CDHEs are also observed in China (Wu et al., 2019a; Wu et al., 2020; Zhang et al., 2022c). However, decreased frequency and duration are observed in some parts of China (e.g., central-east China) (Chen et al., 2019a; Zhang et al., 2022c; Zhou and Liu, 2018). In South Asia or India, increased frequency and spatial extent in CDHEs are observed (Ganguli, 2022; Guntu and Agarwal, 2021; Sharma and Mujumdar, 2017).

In Australia, the increase in the frequency of CDHEs is observed in recent decades, though the trend may vary for different regions or study periods. An increase in months with low precipitation and high temperature (or frequency of CDHEs) over the past 150 years is observed in southeast Australia (Kirono et al., 2017). The increase in the frequency of CDHEs is more remarkable in recent decades. For example, the frequency of CDHEs is observed to be relatively stable during1889-1989 but significantly increases between 1990 and 2019 in Australia (Collins, 2021). Lengthened duration and increased severity are also observed in Australia during 1958-2019, especially in eastern regions (Reddy et al., 2022).

In South America, increased frequency of compound summer droughts and heatwaves is observed in large regions during the past fourty years, including southeast Brazil (Geirinhas et al., 2021) and Amazonia (Costa et al., 2022). For example, over

Amazonia, ten of the most extreme heat waves (longest and most intense) identified in the southeastern Amazonia during 1979 to 2018 are all accompanied by an extreme drying conditions (based on relative humidity and evaporative fraction anomalies), and 9 of these extremes occurred in the last decade, implying increased frequency of CDHEs (Costa et al., 2022). In the Pantanal, increased occurrences of individual droughts and heatwaves in recent decades imply an increase in the frequency of CDHEs during 2001–2020 (Libonati et al., 2022).

In Europe, an increased frequency of CDHEs is observed, especially in the central and southern regions (Ionita and Nagavciuc, 2021). The probability of long dry periods (days with precipitation below 1 mm) and high temperatures has increased (with decreased return period) during 1984–2013 compared with the reference period 1950–1979 in Europe (Manning et al., 2019). Over Spanish mountains, an increase in the frequency of dry-warm days is observed from 1970 to 2007 (Morán-Tejeda et al., 2013). At the decadal scale, an increase in the frequency of CDHEs is observed in the period 2011–2020 compared with previous decades from 1951, especially in central and south-eastern Europe (Ionita et al., 2021), such as Romania (Nagavciuc et al., 2022). Over the Mediterranean region, available evidence indicates an increasing trend in the frequency of CDHEs (De Luca et al., 2020; Lemus-Canovas, 2022; Vogel et al., 2021a). However, in parts of northern Europe, a tendency of decrease in the frequency of CDHEs in noted in several studies, which is likely associated with an increasing precipitation trend (Bezak and Mikoš, 2020; Ionita et al., 2021; Wang et al., 2021b).

In North America, there is evidence of increased frequency and 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 of the United States (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, southeast Europe, and parts of northeast Asia (as shown in Fig. 8). At the regional scale, changed correlations between droughts and temperature 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 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 is not well reproduced by climate models (Hao et al., 2019c). The comparisons of the CMIP5 and CMIP6 in simulating the 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., 2022; 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 answers 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) or 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 influences 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, which include all forcings (ALL) and natural forcings (NAT) experiments, 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 (by comparing results from the historical and natural forcing experiments) 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 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 northeast 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 northeast 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 (hist-nat) 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), which can be assessed through the lens of a compound perspective, 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 many 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 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 Global Climate Model 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), seasonal (Wu et al., 2021c; Zhan et al., 2020; Zscheischler and Seneviratne, 2017), and annual time scales (Meng et al., 2022b; Sarhadi et al., 2018). In many land 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 at the annual scale 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 indicate 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, 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 (i.e., moderate and high emission scenarios, respectively), 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, 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 resource 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 hydrologic droughts in the following season (e.g., warmth 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.; Van Tiel et al., 2021).

The combined impact of the co-occurrence of precipitation deficits and warm periods has been shown to induce reduced runoff (or river flow, water resources) at annual or decadal scales (Brunner et al., 2021c; Hettiarachchi et al.; 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 deficit), 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 (or evapotranspiration) 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, both of which first increases with temperature and then decrease beyond a certain temperature threshold (von Buttlar et al., 2018), and indirectly affect vegetation growth through increasing vapor pressure deficit 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 temperatures, 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., 2021; 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., 2021; Nicolai-Shaw et al., 2017; O et al., 2022; 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 more than 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; O et al., 2022). 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 compound 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 CO_2 under global warming may increase terrestrial ecosystem productivity (Alan Williams, 2014). Recent analyses suggest that the effects of elevated CO_2 (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; Schauberger 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; Schauberger 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 shorterning 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 CO_2 uptake) and enhanced root growth (reduced above-ground biomass) due to increased atmospheric water demand and depleted soil water (Lesk and Anderson, 2021; Schauberger 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) (Matiu 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; Matiu 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 that individual dry conditions or hot conditions across top 5 maize-producing countries (Feng et al., 2019). Irrigation has been 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 (Kemter 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 compound droughts and heatwaves. 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 (RH), 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 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).

Overall, the long-term and high-quality data are existing challenges faced in 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 the different data sources may lead to differences in changes detection in droughts or hot extremes (Hoffmann et al., 2020; Mukherjee and Mishra) 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., mode 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 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; 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 indictor 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 the CDHEs from a multivariate approach or 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, the CDHEs can results from the blocking of anticyclones and soil moisture–temperature feedbacks, while at seasonal or longer time scales, the mode of variability play 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 the climate model 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 the human activities with CDHEs (e.g., irrigation, land use changes) 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 T-P 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 in 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 necessitate 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; Sarhadi 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 sectors, to improve the resilience to cope with compound extremes under global warming.

11 Acknowledgments

This work is supported by the National Key R&D Program of China (2020YFA0608202). The monthly precipitation and temperature data at the global scale from the Climate Research Unit (CRU), University of Delaware (UDEL) and Princeton University's Global Meteorological Forcing Dataset (PGF) were obtained from the website: http://www.cru.uea.ac.uk/data/, https://psl.noaa.gov/data/gridded/, and https://hydrology.princeton.edu/data/pgf/v2/, respectively. The simulated monthly precipitation and temperature data at the global scale from the Coupled Model Intercomparison Project Phase 6 (CMIP6) were obtained from the website: https://esgf-node.llnl.gov/projects/cmip6/.

12 References

Abatzoglou, J.T., Dobrowski, S.Z., Parks, S.A., 2020. Multivariate climate departures have outpaced univariate changes across global lands. Sci. Rep. 10(1), 3891.

Abatzoglou, J.T., Williams, A.P., 2016. Impact of anthropogenic climate change on wildfire across western US forests. Proc. Natl. Acad. Sci. 113(42), 11770-11775.

Abbasian, M.S., Najafi, M.R., Abrishamchi, A., 2021. Increasing risk of meteorological drought in the Lake Urmia basin under climate change: introducing the precipitation–temperature deciles index. J. Hydrol. 592, 125586.

Adler, R.F., Gu, G., Wang, J.J., Huffman, G.J., Curtis, S., Bolvin, D., 2008. Relationships between global precipitation and surface temperature on interannual and longer timescales (1979–2006). J. Geophys. Res-Atmos. 113(D22), D22104.

AghaKouchak, A., Cheng, L., Mazdiyasni, O., Farahmand, A., 2014. Global warming and changes in risk of concurrent climate extremes: insights from the 2014 California drought. Geophys. Res. Lett. 41(24), 8847-8852.

Aihaiti, A., Jiang, Z., Zhu, L., Li, W., You, Q., 2021. Risk changes of compound temperature and precipitation extremes in China under 1.5 °C and 2 °C global warming. Atmos. Res. 264, 105838.

Alan Williams, C., 2014. Heat and drought extremes likely to stress ecosystem productivity equally or more in a warmer, CO_2 rich future. Environ. Res. Lett. 9(10), 101002.

Alexander, L., 2011. Extreme heat rooted in dry soils. Nat. Geosci. 4(1), 12-13.

Ali, S.M., Martius, O., Röthlisberger, M., 2021. Recurrent Rossby Wave packets modulate the persistence of dry and wet spells across the globe. Geophys. Res. Lett. 48(5), e2020GL091452.

Alizadeh, M.R., Adamowski, J., Nikoo, M.R., AghaKouchak, A., Dennison, P., Sadegh, M., 2020. A century of observations reveals increasing likelihood of continental-scale compound dry-hot extremes. Sci. Adv. 6(39), eaaz4571.

Allen, C.D., Breshears, D.D., McDowell, N.G., 2015. On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. Ecosphere 6(8), art129.

Ambika, A.K., Mishra, V., 2021. Modulation of compound extremes of low soil moisture and high vapor pressure deficit by irrigation in India. J. Geophys. Res-Atmos. 126(7), e2021JD034529.

Anderegg, W.R.L., Trugman, A.T., Bowling, D.R., Salvucci, G., Tuttle, S.E., 2019. Plant functional traits and climate influence drought intensification and land–atmosphere feedbacks. Proc. Natl. Acad. Sci. 116(28), 14071-14076.

Archer, E.R.M., Landman, W.A., Tadross, M.A., Malherbe, J., Weepener, H., Maluleke, P., Marumbwa, F.M., 2017. Understanding the evolution of the 2014–2016 summer rainfall seasons in southern Africa: key lessons. Clim. Risk Manag. 16, 22-28.

Ault, T.R., 2020. On the essentials of drought in a changing climate. Science 368(6488), 256-260.

Baldwin, J.W., Dessy, J.B., Vecchi, G.A., Oppenheimer, M., 2019. Temporally compound heat wave events and global warming: an emerging hazard. Earth's Future 7(4), 411–427.

Bandyopadhyay, N., Bhuiyan, C., Saha, A.K., 2016. Heat waves, temperature extremes and their impacts on monsoon rainfall and meteorological drought in Gujarat, India. Nat. Hazards 82(1), 367-388.

Barrucand, M., Vargas, W., Bettolli, M.L., 2014. Warm and cold dry months and associated circulation in the humid and semi-humid Argentine region. Meteorol. Atmos. Phys. 123(3), 143-154.

Basso, B., Ritchie, J., 2014. Temperature and drought effects on maize yield. Nat. Clim. Change. 4(4), 233-233.

Bastos, A., Ciais, P., Friedlingstein, P., Sitch, S., Pongratz, J., Fan, L., Wigneron, J.P., Weber, U., Reichstein, M., Fu, Z., Anthoni, P., Arneth, A., Haverd, V., Jain, A.K., Joetzjer, E., Knauer, J., Lienert, S., Loughran, T., McGuire, P.C., Tian, H., Viovy, N., Zaehle, S., 2020. Direct and seasonal legacy effects of the 2018 heat wave and drought on European ecosystem productivity. Sci. Adv. 6(24), eaba2724.

Bastos, A., Gouveia, C.M., Trigo, R.M., Running, S.W., 2014. Analysing the spatio-temporal impacts of the 2003 and 2010 extreme heatwaves on plant productivity in Europe. Biogeosciences 11(13), 3421-3435.

Bastos, A., Orth, R., Reichstein, M., Ciais, P., Viovy, N., Zaehle, S., Anthoni, P., Arneth, A., Gentine, P., Joetzjer, E., Lienert, S., Loughran, T., McGuire, P.C., O, S., Pongratz, J., Sitch, S., 2021. Vulnerability of European ecosystems to two compound dry and hot summers in 2018 and 2019. Earth Syst. Dynam. 12(4), 1015-1035.

Batibeniz, F., Hauser, M., Seneviratne, S.I., 2022. Countries most exposed to individual and compound extremes at different global warming levels. EGUsphere 2022, 1-26.

Ben-Ari, T., Boé, J., Ciais, P., Lecerf, R., Van der Velde, M., Makowski, D., 2018. Causes and implications of the unforeseen 2016 extreme yield loss in the breadbasket of France. Nat. Commun. 9(1), 1627.

Beniston, M., 2009. Trends in joint quantiles of temperature and precipitation in Europe since 1901 and projected for 2100. Geophys. Res. Lett. 36(7), L07707.

Benson, D.O., Dirmeyer, P.A., 2021. Characterizing the relationship between temperature and soil moisture extremes and their role in the exacerbation of heat waves over the contiguous United States. J. Climate 34(6), 2175-2187.

Berg, A., Findell, K., Lintner, B., Giannini, A., Seneviratne, S.I., Van Den Hurk, B., Lorenz, R., Pitman, A., Hagemann, S., Meier, A., 2016. Land-atmosphere feedbacks amplify aridity increase over land under global warming. Nat. Clim. Change. 6, 869–874.

Berg, A., Lintner, B.R., Findell, K., Seneviratne, S.I., Hurk, B.v.d., Ducharne, A., Chéruy, F., Hagemann, S., Lawrence, D.M., Malyshev, S., Meier, A., Gentine, P., 2015. Interannual coupling between summertime surface temperature and precipitation over land: processes and implications for climate change. J. Climate 28(3), 1308-1328.

Berkovic, S., Raveh-Rubin, S., 2022. Persistent warm and dry extremes over the eastern Mediterranean during winter: The role of North Atlantic blocking and central Mediterranean cyclones. Q. J. R. Meteorol. Soc. 148(746), 2384-2409.

Bevacqua, E., De Michele, C., Manning, C., Couasnon, A., Ribeiro, A.F.S., Ramos, A.M., Vignotto, E., Bastos, A., Blesić, S., Durante, F., Hillier, J., Oliveira, S.C., Pinto, J.G., Ragno, E., Rivoire, P., Saunders, K., van der Wiel, K., Wu, W., Zhang, T., Zscheischler, J., 2021. Guidelines for studying diverse types of compound weather and climate events. Earth's Future 9(11), e2021EF002340.

Bevacqua, E., Maraun, D., Hobæk Haff, I., Widmann, M., Vrac, M., 2017. Multivariate statistical modelling of compound events via pair-copula constructions: analysis of floods in Ravenna (Italy). Hydrol. Earth Syst. Sci. 21(6), 2701-2723.

Bevacqua, E., Zappa, G., Lehner, F., Zscheischler, J., 2022. Precipitation trends determine future occurrences of compound hot–dry events. Nat. Clim. Change. 12(4), 350-355.

Bezak, N., Mikoš, M., 2020. Changes in the compound drought and extreme heat occurrence in the 1961–2018 period at the European scale. Water 12(12), 3543.

Bindoff, N.L., Stott, P.A., AchutaRao, K.M., Allen, M.R., Gillett, N., Gutzler, D., Hansingo, K., Hegerl, G., Hu, Y., Jain, S., 2013. Detection and attribution of climate change: from global to regional, Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 867-952.

Birami, B., Nägele, T., Gattmann, M., Preisler, Y., Gast, A., Arneth, A., Ruehr, N.K., 2020. Hot drought reduces the effects of elevated CO2 on tree water-use efficiency and carbon metabolism. New Phytol. 226(6), 1607-1621.

Bladé, I., Liebmann, B., Fortuny, D., van Oldenborgh, G.J., 2012. Observed and simulated impacts of the summer NAO in Europe: implications for projected drying in the Mediterranean region. Clim. Dynam. 39(3-4), 709-727.

Bouwer, L.M., Cheong, S.-M., Jacot Des Combes, H., Frölicher, T.L., McInnes, K.L., Ratter, B.M.W., Rivera-Arriaga, E., 2022. Risk management and adaptation for extremes and abrupt changes in climate and oceans: current knowledge gaps. Front. Clim. 3, 785641.

Brás, T.A., Seixas, J., Carvalhais, N., Jägermeyr, J., 2021. Severity of drought and heatwave crop losses tripled over the last five decades in Europe. Environ. Res. Lett. 16(6), 065012.

Brouillet, A., Joussaume, S., 2019. Investigating the role of the relative humidity in the co-occurrence of temperature and heat stress extremes in CMIP5 projections. Geophys. Res. Lett. 46(20), 11435–11443.

Brunet, M., Jones, P., 2011. Data rescue initiatives: bringing historical climate data into the 21st century. Climate Res. 47(1-2), 29-40.

Brunner, M.I., Gilleland, E., Wood, A.W., 2021a. Space–time dependence of compound hot–dry events in the United States: assessment using a multi-site multi-variable weather generator. Earth Syst. Dynam. 12(2), 621-634.

Brunner, M.I., Slater, L., Tallaksen, L.M., Clark, M., 2021b. Challenges in modeling and predicting floods and droughts: a review. WIREs Water 8(3), e1520.

Brunner, M.I., Swain, D.L., Gilleland, E., Wood, A.W., 2021c. Increasing importance of temperature as a contributor to the spatial extent of streamflow drought. Environ. Res. Lett. 16(2), 024038.

Bumbaco, K.A., Mote, P.W., 2010. Three recent flavors of drought in the Pacific Northwest. J. Appl. Meteorol. Climatol . 49(9), 2058-2068.

Buras, A., Rammig, A., Zang, C.S., 2020. Quantifying impacts of the drought 2018 on European ecosystems in comparison to 2003. Biogeosciences 17(6), 1655–1672.

Burls, N.J., Blamey, R.C., Cash, B.A., Swenson, E.T., Fahad, A.a., Bopape, M.-J.M., Straus, D.M., Reason, C.J.C., 2019. The Cape Town “Day Zero” drought and Hadley cell expansion. npj Clim. Atmos. Sci. 2(1), 27.

Byers, E., Gidden, M., Leclère, D., Balkovic, J., Burek, P., Ebi, K., Greve, P., Grey, D., Havlik, P., Hillers, A., Johnson, N., Kahil, T., Krey, V., Langan, S., Nakicenovic, N., Novak, R., Obersteiner, M., Pachauri, S., Palazzo, A., Parkinson, S., Rao, N.D., Rogelj, J., Satoh, Y., Wada, Y., Willaarts, B., Riahi, K., 2018. Global exposure and vulnerability to multi-sector development and climate change hotspots. Environ. Res. Lett. 13(5), 055012.

Cannon, A.J., 2016. Multivariate bias correction of climate model output: matching marginal distributions and intervariable dependence structure. J. Climate 29(19), 7045-7064.

Cannon, A.J., 2018. Multivariate quantile mapping bias correction: an N-dimensional probability density function transform for climate model simulations of multiple variables. Clim. Dynam. 50(1), 31-49.

Chang, F.-C., Wallace, J.M., 1987. Meteorological conditions during heat waves and droughts in the United States Great Plains. Mon. Wea. Rev. 115(7), 1253-1269.

Chen, D., Rodhe, H., Emanuel, K., Seneviratne, S.I., Zhai, P., Allard, B., Berg, P., Björck, S., Brown, I.A., Bärring, L., Chafik, L., Deng, K., Gaillard-Lemdahl, M.-J., Hieronymus, M., Kjellström, E., Linderholm, H.W., May, W., Näslund, J.-O., Ou, T., Rutgersson, A., Sahlee, E., Schenk, F., Sjolte, J., Sporre, M.K., Stigebrandt, A., Weyhenmeyer, G.A., Zhang, P., Zhang, Q., 2020. Summary of a workshop on extreme weather events in a warming world organized by the Royal Swedish Academy of Sciences. Tellus B: Chem. Phys. Meteorol. 72(1), 1-13.

Chen, H., Sun, J., 2017. Anthropogenic warming has caused hot droughts more frequently in China. J. Hydrol. 544, 306-318.

Chen, J., Arsenault, R., Brissette, F.P., Zhang, S., 2021a. Climate change impact studies: should we bias correct climate model outputs or post-process impact model outputs? Water Resour. Res. 57(5), e2020WR028638.

Chen, L., Chen, X., Cheng, L., Zhou, P., Liu, Z., 2019a. Compound hot droughts over China: identification, risk patterns and variations. Atmos. Res. 227, 210-219.

Chen, W., Zhu, D., Huang, C., Ciais, P., Yao, Y., Friedlingstein, P., Sitch, S., Haverd, V., Jain, A.K., Kato, E., Kautz, M., Lienert, S., Lombardozzi, D., Poulter, B., Tian, H., Vuichard, N., Walker, A.P., Zeng, N., 2019b. Negative extreme events in gross primary productivity and their drivers in China during the past three decades. Agric. For. Meteorol. 275, 47-58.

Chen, Y., Liao, Z., Shi, Y., Tian, Y., Zhai, P., 2021b. Detectable increases in sequential flood-heatwave events across China during 1961–2018. Geophys. Res. Lett. 48(6), e2021GL092549.

Chen, Y., Moufouma-Okia, W., Masson-Delmotte, V., Zhai, P., Pirani, A., 2018. Recent progress and emerging topics on weather and climate extremes since the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Annu. Rev. Environ. Resour. 43(1), 35-59.

Cheng, L., Hoerling, M., AghaKouchak, A., Livneh, B., Quan, X.-W., Eischeid, J., 2016. How has human-induced climate change affected california drought risk? J. Climate 29(1), 111-120.

Chiang, F., Cook, B.I., McDermid, S., Marvel, K., Schmidt, G.A., Nazarenko, L.S., Kelley, M., 2022a. Responses of compound daytime and nighttime warm-dry and warm-humid events to individual anthropogenic forcings. Environ. Res. Lett. 17(8), 084015.

Chiang, F., Greve, P., Mazdiyasni, O., Wada, Y., AghaKouchak, A., 2021. A multivariate conditional probability ratio framework for the detection and attribution of compound climate extremes. Geophys. Res. Lett. 48(15), e2021GL094361.

Chiang, F., Greve, P., Mazdiyasni, O., Wada, Y., AghaKouchak, A., 2022b. Intensified likelihood of concurrent warm and dry months attributed to anthropogenic climate change. Water Resour. Res. 58(6), e2021WR030411.

Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogee, J., Allard, V., Aubinet, M., Buchmann, N., Bernhofer, C., Carrara, A., Chevallier, F., De Noblet, N., Friend, A.D., Friedlingstein, P., Grunwald, T., Heinesch, B., Keronen, P., Knohl, A., Krinner, G., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourcival, J.M., Papale, D., Pilegaard, K., Rambal, S., Seufert, G., Soussana, J.F., Sanz, M.J., Schulze, E.D., Vesala, T., Valentini, R., 2005. Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature 437(7058), 529-533.

Coffel, E.D., Keith, B., Lesk, C., Horton, R.M., Bower, E., Lee, J., Mankin, J.S., 2019. Future hot and dry rears worsen Nile basin water scarcity despite projected precipitation increases. Earth's Future 7(8), 967-977.

Cohen, I., Zandalinas, S.I., Huck, C., Fritschi, F.B., Mittler, R., 2021. Meta-analysis of drought and heat stress combination impact on crop yield and yield components. Physiol. Plantarum. 171(1), 66-76.

Collins, B., 2021. Frequency of compound hot–dry weather extremes has significantly increased in Australia since 1889. J. Agron. Crop Sci., 1-15.

Cook, B.I., Smerdon, J.E., Seager, R., Coats, S., 2014. Global warming and 21st century drying. Clim. Dynam. 43(9-10), 2607-2627.

Costa, D.F., Gomes, H.B., Silva, M.C.L., Zhou, L., 2022. The most extreme heat waves in Amazonia happened under extreme dryness. Clim. Dynam. 59(1), 281-295.

Coumou, D., Di Capua, G., Vavrus, S., Wang, L., Wang, S., 2018. The influence of Arctic amplification on mid-latitude summer circulation. Nat. Commun. 9(1), 2959-2959.

Coumou, D., Robinson, A., Rahmstorf, S., 2013. Global increase in record-breaking monthly-mean temperatures. Clim. Change 118(3), 771-782.

Cowan, T., Hegerl, G.C., Colfescu, I., Bollasina, M., Purich, A., Boschat, G., 2017. Factors contributing to record-breaking heat waves over the great plains during the 1930s dust bowl. J. Climate 30(7), 2437-2461.

Crhová, L., Holtanová, E., 2018. Simulated relationship between air temperature and precipitation over Europe: sensitivity to the choice of RCM and GCM. Int. J. Climatol. 38(3), 1595-1604.

Crockett, J.L., Westerling, A.L., 2018. Greater temperature and precipitation extremes intensify western U.S. droughts, wildfire severity, and Sierra Nevada tree mortality. J. Climate 31(1), 341-354.

Cutter, S.L., 2018. Compound, cascading, or complex disasters: what's in a name? Environment: Science and Policy for Sustainable Development 60(6), 16-25.

Dai, A., 2013. Increasing drought under global warming in observations and models. Nat. Clim. Change. 3(1), 52-58.

Dai, A., Zhao, T., Chen, J., 2018. Climate change and drought: a precipitation and evaporation perspective. Curr. Clim. Change Rep. 4(3), 301-312.

Dannenberg, M.P., Yan, D., Barnes, M.L., Smith, W.K., Johnston, M.R., Scott, R.L., Biederman, J.A., Knowles, J.F., Wang, X., Duman, T., Litvak, M.E., Kimball, J.S., Williams, A.P., Zhang, Y., 2022. Exceptional heat and atmospheric dryness amplified losses of primary production during the 2020 U.S. Southwest hot drought. Global. Change. Biol. 28(16), 4794-4806.

Das, J., Manikanta, V., Umamahesh, N.V., 2022. Population exposure to compound extreme events in India under different emission and population scenarios. Sci. Total. Environ. 806, 150424.

Das, T., Pierce, D.W., Cayan, D.R., Vano, J.A., Lettenmaier, D.P., 2011. The importance of warm season warming to western U.S. streamflow changes. Geophys. Res. Lett. 38(23), L23403.

de Brito, M.M., 2021. Compound and cascading drought impacts do not happen by chance: a proposal to quantify their relationships. Sci. Total. Environ. 778, 146236.

De Luca, P., Messori, G., Faranda, D., Ward, P.J., Coumou, D., 2020. Compound warm–dry and cold–wet events over the Mediterranean. Earth Syst. Dynam. 11(3), 793-805.

de Ruiter, M.C., Couasnon, A., van den Homberg, M.J.C., Daniell, J.E., Gill, J.C., Ward, P.J., 2020. Why we can no longer ignore consecutive disasters. Earth's Future 8(3), e2019EF001425.

Deb, P., Moradkhani, H., Abbaszadeh, P., Kiem, A.S., Engström, J., Keellings, D., Sharma, A., 2020. Causes of the widespread 2019–2020 Australian bushfire season. Earth's Future 8(11), e2020EF001671.

Deng, K.-Q., Azorin-Molina, C., Yang, S., Hu, C.-D., Zhang, G.-F., Minola, L., Vicente-Serrano, S., Chen, D., 2022. Shifting of summertime weather extremes in Western Europe during the last decade. Adv. Clim. Change Res. 13(2), 218-227.

Deser, C., Lehner, F., Rodgers, K.B., Ault, T., Delworth, T.L., DiNezio, P.N., Fiore, A., Frankignoul, C., Fyfe, J.C., Horton, D.E., Kay, J.E., Knutti, R., Lovenduski, N.S., Marotzke, J., McKinnon, K.A., Minobe, S., Randerson, J., Screen, J.A., Simpson, I.R., Ting, M., 2020. Insights from Earth system model initial-condition large ensembles and future prospects. Nat. Clim. Change. 10(4), 277-286.

Di Luca, A., de Elía, R., Bador, M., Argüeso, D., 2020. Contribution of mean climate to hot temperature extremes for present and future climates. Weather Clim. Extrem. 28, 100255.

Diffenbaugh, N.S., Pal, J.S., Trapp, R.J., Giorgi, F., 2005. Fine-scale processes regulate the response of extreme events to global climate change. Proc. Natl. Acad. Sci. 102(44), 15774-15778.

Diffenbaugh, N.S., Swain, D.L., Touma, D., 2015. Anthropogenic warming has increased drought risk in California. Proc. Natl. Acad. Sci. 112(13), 3931-3936.

Dirmeyer, P.A., Balsamo, G., Blyth, E.M., Morrison, R., Cooper, H.M., 2021. Land-atmosphere interactions exacerbated the drought and heatwave over northern europe during summer 2018. AGU Advances 2(2), e2020AV000283.

Dirmeyer, P.A., Jin, Y., Singh, B., Yan, X., 2013. Trends in land–atmosphere interactions from CMIP5 simulations. J. Hydrometeorol. 14(3), 829-849.

Dong, L., Mitra, C., Greer, S., Burt, E., 2018. The dynamical linkage of atmospheric blocking to drought, heatwave and urban heat island in southeastern US: a multi-scale case study. Atmosphere 9(1), 33.

Drakes, O., Tate, E., 2022. Social vulnerability in a multi-hazard context: a systematic review. Environ. Res. Lett. 17(3), 033001.

Du, H., Wu, Z., Jin, Y., Zong, S., Meng, X., 2013. Quantitative relationships between precipitation and temperature over Northeast China, 1961–2010. Theor. Appl. Climatol. 113(3-4), 659-670.

Estrella, N., Menzel, A., 2013. Recent and future climate extremes arising from changes to the bivariate distribution of temperature and precipitation in Bavaria, Germany. Int. J. Climatol. 33(7), 1687–1695.

Eyring, V., Bony, S., Meehl, G.A., Senior, C.A., Stevens, B., Stouffer, R.J., Taylor, K.E., 2016. Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. Geosci. Model Dev. 9(5), 1937-1958.

Fahad, S., Bajwa, A.A., Nazir, U., Anjum, S.A., Farooq, A., Zohaib, A., Sadia, S., Nasim, W., Adkins, S., Saud, S., Ihsan, M.Z., Alharby, H., Wu, C., Wang, D., Huang, J., 2017. Crop production under drought and heat stress: plant responses and management options. Front. Plant Sci. 8, 1147.

Fang, B., Lu, M., 2020. Heatwave and blocking in the Northeastern Asia: occurrence, variability, and association. J. Geophys. Res-Atmos. 125(6), e2019JD031627.

Fasullo, J., Otto-Bliesner, B., Stevenson, S., 2018. ENSO's changing influence on temperature, precipitation, and wildfire in a warming climate. Geophys. Res. Lett. 45(17), 9216-9225.

Feng, S., Hao, Z., 2020. Quantifying likelihoods of extreme occurrences causing maize yield reduction at the global scale. Sci. Total. Environ. 704, 135250.

Feng, S., Hao, Z., 2021. Quantitative contribution of ENSO to precipitation-temperature dependence and associated compound dry and hot events. Atmos. Res. 260, 105695.

Feng, S., Hao, Z., Wu, X., Zhang, X., Hao, F., 2021a. A multi-index evaluation of changes in compound dry and hot events of global maize areas. J. Hydrol. 602, 126728.

Feng, S., Hao, Z., Zhang, X., Hao, F., 2019. Probabilistic evaluation of the impact of compound dry-hot events on global maize yields. Sci. Total. Environ. 689, 1228-1234.

Feng, S., Hao, Z., Zhang, X., Wu, L., Zhang, Y., Hao, F., 2022. Climate change impacts on concurrences of hydrological droughts and high temperature extremes in a semi-arid river basin of China. J. Arid Environ. 202, 104768.

Feng, S., Wu, X., Hao, Z., Hao, Y., Zhang, X., Hao, F., 2020. A database for characteristics and variations of global compound dry and hot events. Weather Clim. Extrem. 30, 100299.

Feng, Y., Liu, W., Sun, F., Wang, H., 2021b. Changes of compound hot and dry extremes on different land surface conditions in China during 1957–2018. Int. J. Climatol. 41(S1), E1085– E1099.

Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D., Ebi, K., Mastrandrea, M., Mach, K., Plattner, G., Allen, S., 2012. Managing the risks of extreme events and disasters to advance climate change adaptation. A Special Report of

Working Groups I and II of the Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge, UK

Findell, K.L., Berg, A., Gentine, P., Krasting, J.P., Lintner, B.R., Malyshev, S., Santanello, J.A., Shevliakova, E., 2017. The impact of anthropogenic land use and land cover change on regional climate extremes. Nat. Commun. 8(1), 989.

Fink, A.H., Brücher, T., Krüger, A., Leckebusch, G.C., Pinto, J.G., Ulbrich, U., 2004. The 2003 European summer heatwaves and drought –synoptic diagnosis and impacts. Weather 59(8), 209-216.

Fischer, E.M., Knutti, R., 2015. Anthropogenic contribution to global occurrence of heavy-precipitation and high-temperature extremes. Nat. Clim. Change. 5, 560.

Fischer, E.M., Seneviratne, S.I., Vidale, P.L., Lüthi, D., Schär, C., 2007. Soil moisture–atmosphere interactions during the 2003 European summer heat wave. J. Climate 20(20), 5081-5099.

Fischer, E.M., Sippel, S., Knutti, R., 2021. Increasing probability of record-shattering climate extremes. Nat. Clim. Change. 11(8), 689-695.

Flach, M., Brenning, A., Gans, F., Reichstein, M., Sippel, S., Mahecha, M.D., 2021. Vegetation modulates the impact of climate extremes on gross primary production. Biogeosciences 18(1), 39-53.

Flach, M., Gans, F., Brenning, A., Denzler, J., Reichstein, M., Rodner, E., Bathiany, S., Bodesheim, P., Guanche, Y., Sippel, S., Mahecha, M.D., 2017. Multivariate anomaly detection for Earth observations: a comparison of algorithms and feature extraction techniques. Earth Syst. Dynam. 8(3), 677-696.

Flach, M., Sippel, S., Gans, F., Bastos, A., Brenning, A., Reichstein, M., Mahecha, M.D., 2018. Contrasting biosphere responses to hydrometeorological extremes: revisiting the 2010 western Russian heatwave. Biogeosciences 15(20), 6067-6085.

Floriancic, M.G., Berghuijs, W.R., Molnar, P., Kirchner, J.W., 2021. Seasonality and drivers of low flows across Europe and the United States. Water Resour. Res. 57(9), e2019WR026928.

Fortin, G., Hétu, B., 2014. Estimating winter trends in climatic variables in the Chic-Chocs Mountains, Canada (1970–2009). Int. J. Climatol. 34(10), 3078-3088.

François, B., Vrac, M., Cannon, A.J., Robin, Y., Allard, D., 2020. Multivariate bias corrections of climate simulations: which benefits for which losses? Earth Syst. Dynam. 11(2), 537-562.

Freychet, N., Hegerl, G., Mitchell, D., Collins, M., 2021. Future changes in the frequency of temperature extremes may be underestimated in tropical and subtropical regions. Commun. Earth Environ. 2(1), 28.

Gallant, A.J., Karoly, D.J., 2010. A combined climate extremes index for the Australian region. J. Climate 23(23), 6153-6165.

Gallant, A.J., Karoly, D.J., Gleason, K.L., 2014. Consistent trends in a modified climate extremes index in the United States, Europe, and Australia. J. Climate 27(4), 1379-1394.

Gampe, D., Zscheischler, J., Reichstein, M., O'Sullivan, M., Smith, W.K., Sitch, S., Buermann, W., 2021. Increasing impact of warm droughts on northern ecosystem productivity over recent decades. Nat. Clim. Change. 11, 772–779.

Ganguli, P., 2022. Amplified risk of compound heat stress-dry spells in Urban India. Clim. Dynam. in press.

García-Herrera, R., Díaz, J., Trigo, R.M., Luterbacher, J., Fischer, E.M., 2010. A review of the European summer heat wave of 2003. Crit. Rev. Env. Sci. Tec 40(4), 267-306.

Gebremeskel Haile, G., Tang, Q., Sun, S., Huang, Z., Zhang, X., Liu, X., 2019. Droughts in east africa: causes, impacts and resilience. Earth Sci. Rev. 193, 146-161.

Geirinhas, J.L., Russo, A., Libonati, R., Sousa, P.M., Miralles, D.G., Trigo, R.M., 2021. Recent increasing frequency of compound summer drought and heatwaves in Southeast Brazil. Environ. Res. Lett. 16(3), 034036.

Geirinhas, J.L., Russo, A.C., Libonati, R., Miralles, D.G., Sousa, P.M., Wouters, H., Trigo, R.M., 2022. The influence of soil dry-out on the record-breaking hot 2013/2014 summer in Southeast Brazil. Sci. Rep. 12(1), 5836.

Gevaert, A.I., Miralles, D.G., de Jeu, R.A.M., Schellekens, J., Dolman, A.J., 2018. Soil moisture-temperature coupling in a set of land surface models. J. Geophys. Res-Atmos. 123(3), 1481– 1498.

Gibson, P.B., Pitman, A.J., Lorenz, R., Perkins-Kirkpatrick, S.E., 2017. The role of circulation and land surface conditions in current and future Australian heat waves. J. Climate 30(24), 9933-9948.

Gill, J.C., Malamud, B.D., 2014. Reviewing and visualizing the interactions of natural hazards. Rev. Geophys. 52(4), 680-722.

Gillett, N.P., Shiogama, H., Funke, B., Hegerl, G., Knutti, R., Matthes, K., Santer, B.D., Stone, D., Tebaldi, C., 2016. The Detection and Attribution Model Intercomparison Project (DAMIP v1.0) contribution to CMIP6. Geosci. Model Dev. 9(10), 3685-3697.

Gissing, A., Timms, M., Browning, S., Crompton, R., McAneney, J., 2022. Compound natural disasters in Australia: a historical analysis. Environ. Hazards 21(2), 159-173.

Gleason, K.L., Lawrimore, J.H., Levinson, D.H., Karl, T.R., Karoly, D.J., 2008. A revised US climate extremes index. J. Climate 21(10), 2124-2137.

Glotter, M., Elliott, J., 2016. Simulating US agriculture in a modern Dust Bowl drought. Nat. Plants 3(1), 16193.

Goulart, H.M.D., van der Wiel, K., Folberth, C., Balkovic, J., van den Hurk, B., 2021. Storylines of weather-induced crop failure events under climate change. Earth Syst. Dynam. 12(4), 1503–1527.

Grossiord, C., Gessler, A., Reed, S.C., Borrego, I., Collins, A.D., Dickman, L.T., Ryan, M., Schönbeck, L., Sevanto, S., Vilagrosa, A., McDowell, N.G., 2018. Reductions in tree performance during hotter droughts are mitigated by shifts in nitrogen cycling. Plant Cell Environ. 41(11), 2627-2637.

Gruber, N., Boyd, P.W., Frölicher, T.L., Vogt, M., 2021. Biogeochemical extremes and compound events in the ocean. Nature 600(7889), 395-407.

Guntu, R.K., Agarwal, A., 2021. Disentangling increasing compound extremes at regional scale during Indian summer monsoon. Sci. Rep. 11(1), 16447.

Guo, Q., Chen, J., Zhang, X.J., Xu, C.-Y., Chen, H., 2020. Impacts of using state-of-the-art multivariate bias correction methods on hydrological modeling over North America. Water Resour. Res. 56(5), e2019WR026659.

Ha, K.-J., Seo, Y.-W., Yeo, J.-H., Timmermann, A., Chung, E.-S., Franzke, C.L.E., Chan, J.C.L., Yeh, S.-W., Ting, M., 2022. Dynamics and characteristics of dry and moist heatwaves over East Asia. npj Clim. Atmos. Sci. 5(1), 49.

Hamed, R., Van Loon, A.F., Aerts, J., Coumou, D., 2021. Impacts of hot-dry compound extremes on US soybean yields. Earth Syst. Dynam. 12(4), 1371-1391.

Hammond, W.M., Williams, A.P., Abatzoglou, J.T., Adams, H.D., Klein, T., López, R., Sáenz-Romero, C., Hartmann, H., Breshears, D.D., Allen, C.D., 2022. Global field observations of tree die-off reveal hotter-drought fingerprint for Earth's forests. Nat. Commun. 13(1), 1761.

Hansen, J., Ruedy, R., Sato, M., Lo, K., 2010. Global surface temperature change. Rev. Geophys. 48(4), RG4004.

Hao, Y., Hao, Z., Feng, S., Wu, X., Zhang, X., Hao, F., 2021b. Categorical prediction of compound dry and hot events in northeast China based on large-scale climate signals. J. Hydrol. 602, 126729.

Hao, Y., Hao, Z., Feng, S., Zhang, X., Hao, F., 2020a. Response of vegetation to El Niño-Southern Oscillation (ENSO) via compound dry and hot events in southern Africa. Glob. Planet. Change 195, 103358.

Hao, Y., Hao, Z., Fu, Y., Feng, S., Zhang, X., Wu, X., Hao, F., 2021. Probabilistic assessments of the impacts of compound dry and hot events on global vegetation during growing seasons. Environ. Res. Lett. 16(7), 074055.

Hao, Z., 2022. Compound events and associated impacts in China. iScience 25(8), 104689.

Hao, Z., AghaKouchak, A., Phillips, T.J., 2013. Changes in concurrent monthly precipitation and temperature extremes. Environ. Res. Lett. 8(3), 034014.

Hao, Z., Hao, F., Singh, V., Zhang, X., 2018a. Changes in the severity of compound drought and hot extremes over global land areas. Environ. Res. Lett. 13(12), 124022.

Hao, Z., Hao, F., Singh, V.P., Ouyang, W., Zhang, X., Zhang, S., 2020b. A joint extreme index for compound droughts and hot extremes. Theor. Appl. Climatol. 142, 321-328.

Hao, Z., Hao, F., Singh, V.P., Xia, Y., Shi, C., Zhang, X., 2018b. A multivariate approach for statistical assessments of compound extremes. J. Hydrol. 565, 87-94.

Hao, Z., Hao, F., Singh, V.P., Zhang, X., 2018c. Quantifying the relationship between compound dry and hot events and El Niño–Southern Oscillation (ENSO) at the global scale. J. Hydrol. 567, 332-338.

Hao, Z., Hao, F., Singh, V.P., Zhang, X., 2019a. Statistical prediction of the severity of compound dry-hot events based on El Niño-Southern Oscillation. J. Hydrol. 572, 243-250.

Hao, Z., Hao, F., Xia, Y., Singh, V., Zhang, X., 2019b. A monitoring and prediction system for compound dry and hot events. Environ. Res. Lett. 14 (11), 114034.

Hao, Z., Li, W., Singh, V.P., Xia, Y., Zhang, X., Hao, F., 2020c. Impact of dependence changes on the likelihood of hot extremes under drought conditions in the United States. J. Hydrol. 581, 124410.

Hao, Z., Phillips, T.J., Hao, F., Wu, X., 2019c. Changes in the dependence between global precipitation and temperature from observations and model simulations. Int. J. Climatol. 39(12), 4895– 4906.

Hao, Z., Singh, V., Hao, F., 2018d. Compound extremes in hydroclimatology: a review. Water 10(6), 718.

Hao, Z., Singh, V.P., 2020. Compound events under global warming: a dependence perspective. J. Hydrol. Eng. 25(9), 03120001.

Hao, Z., Singh, V.P., Xia, Y., 2018e. Seasonal drought prediction: advances, challenges, and future prospects. Rev. Geophys. 56(1), 108–141.

Haqiqi, I., Grogan, D.S., Hertel, T.W., Schlenker, W., 2021. Quantifying the impacts of compound extremes on agriculture. Hydrol. Earth Syst. Sci. 25(2), 551-564.

Hartick, C., Furusho, C., Goergen, K., Kollet, S., 2021. An interannual probabilistic assessment of subsurface water storage over europe using a fully coupled terrestrial model. Water Resour. Res. 57(1), e2020WR027828.

He, B., Wang, H.L., Wang, Q.F., Di, Z.H., 2015. A quantitative assessment of the relationship between precipitation deficits and air temperature variations. J. Geophys. Res-Atmos. 120(12), 5951-5961.

He, X., Sheffield, J., 2020. Lagged compound occurrence of droughts and pluvials globally over the past seven decades. Geophys. Res. Lett. 47(14), e2020GL087924.

He, Y., Fang, J., Xu, W., Shi, P., 2022a. Substantial increase of compound droughts and heatwaves in wheat growing seasons worldwide. Int. J. Climatol. 42(10), 5038-5054.

He, Y., Hu, X., Xu, W., Fang, J., Shi, P., 2022b. Increased probability and severity of compound dry and hot growing seasons over world's major croplands. Sci. Total. Environ. 824, 153885.

Hegerl, G.C., Hanlon, H., Beierkuhnlein, C., 2011. Climate science: elusive extremes. Nat. Geosci. 4(3), 142-143.

Heinicke, S., Frieler, K., Jägermeyr, J., Mengel, M., 2022. Global gridded crop models underestimate yield responses to droughts and heatwaves. Environ. Res. Lett. 17(4), 044026.

Herrera-Estrada, J.E., Martinez, J.A., Dominguez, F., Findell, K.L., Wood, E.F., Sheffield, J., 2019. Reduced moisture transport linked to drought propagation across North America. Geophys. Res. Lett. 46(10), 5243-5253.

Herrera-Estrada, J.E., Sheffield, J., 2017. Uncertainties in future projections of summer droughts and heat waves over the contiguous United States. J. Climate 30(16), 6225-6246.

Hettiarachchi, S., Wasko, C., Sharma, A., 2022. Do longer dry spells associated with warmer years compound the stress on global water resources? Earth's Future 10(2), e2021EF002392.

Hillier, J.K., Matthews, T., Wilby, R.L., Murphy, C., 2020. Multi-hazard dependencies can increase or decrease risk. Nat. Clim. Change. 10(7), 595-598.

Hirschi, M., Seneviratne, S.I., Alexandrov, V., Boberg, F., Boroneant, C., Christensen, O.B., Formayer, H., Orlowsky, B., Stepanek, P., 2011. Observational evidence for soil-moisture impact on hot extremes in southeastern Europe. Nat. Geosci. 4(1), 17-21.

Hoegh-Guldberg, O., Jacob, D., Taylor, M., Guillén Bolaños, T., Bindi, M., Brown, S., Camilloni, I.A., Diedhiou, A., Djalante, R., Ebi, K., Engelbrecht, F., Guiot, J., Hijioka, Y., Mehrotra, S., Hope, C.W., Payne, A.J., Pörtner, H.-O., Seneviratne, S.I., Thomas, A., Warren, R., Zhou, G., 2019. The human imperative of stabilizing global climate change at 1.5°C. Science 365(6459), eaaw6974.

Hoffmann, D., Gallant, A.J.E., Arblaster, J.M., 2020. Uncertainties in drought from index and data selection. J. Geophys. Res-Atmos. 125(18), e2019JD031946.

Horton, R.M., Mankin, J.S., Lesk, C., Coffel, E., Raymond, C., 2016. A review of recent advances in research on extreme heat events. Curr. Clim. Change Rep. 2(4), 242-259.

Hsiao, J., Swann, A.L.S., Kim, S.-H., 2019. Maize yield under a changing climate: the hidden role of vapor pressure deficit. Agric. For. Meteorol. 279, 107692.

Hu, L., Luo, J.-J., Huang, G., Wheeler, M.C., 2019. Synoptic features responsible for heat waves in central africa, a region with strong multidecadal trends. J. Climate 32(22), 7951-7970.

Huang, W.K., Monahan, A.H., Zwiers, F.W., 2021. Estimating concurrent climate extremes: a conditional approach. Weather Clim. Extrem., 100332.

Hulme, M., 2014. Attributing weather extremes to ‘climate change’ A review. Prog. Phys. Geog. 38(4), 499-511.

Ionita, M., Caldarescu, D.E., Nagavciuc, V., 2021. Compound hot and dry events in europe: variability and large-scale drivers. Front. Clim. 3(58), 688992.

Ionita, M., Nagavciuc, V., 2021. Changes in drought features at the European level over the last 120 years. Nat. Hazards Earth Syst. Sci. 21(5), 1685-1701.

Ionita, M., Tallaksen, L.M., Kingston, D.G., Stagge, J.H., Laaha, G., Van Lanen, H.A.J., Scholz, P., Chelcea, S.M., Haslinger, K., 2017. The European 2015 drought from a climatological perspective. Hydrol. Earth Syst. Sci. 21(3), 1397-1419.

Jägermeyr, J., Frieler, K., 2018. Spatial variations in crop growing seasons pivotal to reproduce global fluctuations in maize and wheat yields. Sci. Adv. 4(11), eaat4517.

Jin, Z., Zhuang, Q., Wang, J., Archontoulis, S.V., Zobel, Z., Kotamarthi, V.R., 2017. The combined and separate impacts of climate extremes on the current and future US rainfed maize and soybean production under elevated CO2. Global. Change. Biol. 23(7), 2687-2704.

Jones, P.D., New, M., Parker, D.E., Martin, S., Rigor, I.G., 1999. Surface air temperature and its changes over the past 150 years. Rev. Geophys. 37(2), 173-199.

Kadam, N.N., Xiao, G., Melgar, R.J., Bahuguna, R.N., Quinones, C., Tamilselvan, A., Prasad, P.V.V., Jagadish, K.S., 2014. Agronomic and physiological responses to high temperature, drought, and elevated CO2 interactions in cereals. Advances in agronomy 127, 111-156.

Kappes, M.S., Keiler, M., von Elverfeldt, K., Glade, T., 2012. Challenges of analyzing multi-hazard risk: a review. Nat. Hazards 64(2), 1925-1958.

Karl, T.R., Knight, R.W., Easterling, D.R., Quayle, R.G., 1996. Indices of climate change for the United States. Bull. Amer. Meteor. Soc 77(2), 279-292.

Kautz, L.A., Martius, O., Pfahl, S., Pinto, J.G., Ramos, A.M., Sousa, P.M., Woollings, T., 2022. Atmospheric blocking and weather extremes over the Euro-Atlantic sector – a review. Weather Clim. Dynam. 3(1), 305-336.

Keller, D.E., Fischer, A.M., Liniger, M.A., Appenzeller, C., Knutti, R., 2017. Testing a weather generator for downscaling climate change projections over Switzerland. Int. J. Climatol. 37(2), 928-942.

Kemter, M., Fischer, M., Luna, L.V., Schönfeldt, E., Vogel, J., Banerjee, A., Korup, O., Thonicke, K., 2021. Cascading hazards in the aftermath of Australia's 2019/2020 black summer wildfires. Earth's Future 9(3), e2020EF001884.

Kiem, A.S., Johnson, F., Westra, S., van Dijk, A., Evans, J.P., O'Donnell, A., Rouillard, A., Barr, C., Tyler, J., Thyer, M., Jakob, D., Woldemeskel, F., Sivakumar, B., Mehrotra, R., 2016. Natural hazards in Australia: droughts. Clim. Change 139(1), 37-54.

Kingston, D.G., Stagge, J.H., Tallaksen, L.M., Hannah, D.M., 2015. European-scale drought: Understanding connections between atmospheric circulation and meteorological drought indices. J. Climate 28(2), 505-516.

Kirono, D.G.C., Hennessy, K.J., Grose, M., 2017. Increasing risk of months with low rainfall and high temperature in southeast Australia for the past 150 years. Clim. Risk Manag. 16( ), 10-21.

Knutson, T., Kossin, J., Mears, C., Perlwitz, J., Wehner, M., 2017. Detection and attribution of climate change, in: D. J. Wuebbles, D. W. Fahey, K. A. Hibbardet al (Eds.), Climate Science Special Report: Fourth National Climate Assessment, Volume I. . U.S. Global Change Research Program, pp. 114-132.

Kong, Q., Guerreiro, S.B., Blenkinsop, S., Li, X.-F., Fowler, H.J., 2020. Increases in summertime concurrent drought and heatwave in Eastern China. Weather Clim. Extrem. 28, 100242.

Kornhuber, K., Coumou, D., Vogel, E., Lesk, C., Donges, J.F., Lehmann, J., Horton, R.M., 2020. Amplified Rossby waves enhance risk of concurrent heatwaves in major breadbasket regions. Nat. Clim. Change. 10(1), 48-53.

Kornhuber, K., Osprey, S., Coumou, D., Petri, S., Petoukhov, V., Rahmstorf, S., Gray, L., 2019. Extreme weather events in early summer 2018 connected by a recurrent hemispheric wave-7 pattern. Environ. Res. Lett. 14(5), 054002.

Koster, R., Schubert, S., Suarez, M., 2009. Analyzing the concurrence of meteorological droughts and warm periods, with implications for the determination of evaporative regime. J. Climate 22(12), 3331-3341.

López-Moreno, J.I., Vicente-Serrano, S.M., Morán-Tejeda, E., Lorenzo-Lacruz, J., Kenawy, A., Beniston, M., 2011. Effects of the North Atlantic Oscillation (NAO) on combined temperature and precipitation winter modes in the Mediterranean mountains: observed relationships and projections for the 21st century. Glob. Planet. Change 77(1-2), 62-76.

La Sorte, F.A., Johnston, A., Ault, T.R., 2021. Global trends in the frequency and duration of temperature extremes. Clim. Change 166(1), 1.

Lansu, E.M., van Heerwaarden, C.C., Stegehuis, A.I., Teuling, A.J., 2020. Atmospheric aridity and apparent soil moisture drought in european forest during heat waves. Geophys. Res. Lett. 47(6), e2020GL087091.

Lazoglou, G., Anagnostopoulou, C., 2019. Joint distribution of temperature and precipitation in the Mediterranean, using the Copula method. Theor. Appl. Climatol. 135, 1399-1411.

Lehner, F., Deser, C., Maher, N., Marotzke, J., Fischer, E.M., Brunner, L., Knutti, R., Hawkins, E., 2020. Partitioning climate projection uncertainty with multiple large ensembles and CMIP5/6. Earth Syst. Dynam. 11(2), 491-508.

Lemordant, L., Gentine, P., Stéfanon, M., Drobinski, P., Fatichi, S., 2016. Modification of land-atmosphere interactions by CO2 effects: implications for summer dryness and heat wave amplitude. Geophys. Res. Lett. 43(19), 10,240-10,248.

Lemus-Canovas, M., 2022. Changes in compound monthly precipitation and temperature extremes and their relationship with teleconnection patterns in the Mediterranean. J. Hydrol. 608, 127580.

Lemus-Canovas, M., Lopez-Bustins, J.A., 2021. Assessing internal changes in the future structure of dry–hot compound events: the case of the Pyrenees. Nat. Hazards Earth Syst. Sci. 21(6), 1721-1738.

Leng, G., 2019. Uncertainty in assessing temperature impact on US maize yield under global warming: the role of compounding precipitation effect. J. Geophys. Res-Atmos. 124(12), 6238–6246.

Leonard, M., Westra, S., Phatak, A., Lambert, M., van den Hurk, B., McInnes, K., Risbey, J., Schuster, S., Jakob, D., Stafford-Smith, M., 2014. A compound event framework for understanding extreme impacts. Wiley Interdiscip. Rev. Clim. Change 5(1), 113–128.

Lesk, C., Anderson, W., 2021. Decadal variability modulates trends in concurrent heat and drought over global croplands. Environ. Res. Lett. 16(5), 055024.

Lesk, C., Coffel, E., Winter, J., Ray, D., Zscheischler, J., Seneviratne, S.I., Horton, R., 2021. Stronger temperature–moisture couplings exacerbate the impact of climate warming on global crop yields. Nature Food 2(9), 683-691.

Lesk, C., Rowhani, P., Ramankutty, N., 2016. Influence of extreme weather disasters on global crop production. Nature 529, 84.

Lhotka, O., Kyselý, J., 2022. Precipitation–temperature relationships over Europe in CORDEX regional climate models. Int. J. Climatol. 42(9), 4868-4880.

Li, C., Sinha, E., Horton, D.E., Diffenbaugh, N.S., Michalak, A.M., 2014. Joint bias correction of temperature and precipitation in climate model simulations. J. Geophys. Res-Atmos. 119(23), 13,153-13,162.

Li, E., Zhao, J., Pullens, J.W.M., Yang, X., 2022a. The compound effects of drought and high temperature stresses will be the main constraints on maize yield in Northeast China. Sci. Total. Environ. 812, 152461.

Li, H., Chen, H., Sun, B., Wang, H., Sun, J., 2020a. A detectable anthropogenic shift toward intensified summer hot drought events over northeastern China. Earth Space Sci. 7(1), e2019EA000836.

Li, H., Chen, H., Wang, H., Sun, J., Ma, J., 2018a. Can barents sea ice decline in spring enhance summer hot drought events over northeastern China? J. Climate 31(12), 4705-4725.

Li, H., He, S., Gao, Y., Chen, H., Wang, H., 2020b. North Atlantic modulation of interdecadal variations in hot drought events over northeastern China. J. Climate 33(10), 4315-4332.

Li, J., Bevacqua, E., Chen, C., Wang, Z., Chen, X., Myneni, R.B., Wu, X., Xu, C.-Y., Zhang, Z., Zscheischler, J., 2022b. Regional asymmetry in the response of global vegetation growth to springtime compound climate events. Commun. Earth Environ. 3(1), 123.

Li, J., Wang, Z., Wu, X., Zscheischler, J., Guo, S., Chen, X., 2021a. A standardized index for assessing sub-monthly compound dry and hot conditions. Hydrol. Earth Syst. Sci. 25, 1587–1601.

Li, L., Zheng, Z., Biederman, J.A., Qian, R., Ran, Q., Zhang, B., Xu, C., Wang, F., Zhou, S., Che, R., Dong, J., Xu, Z., Cui, X., Hao, Y., Wang, Y., 2020c. Drought and heat wave impacts on grassland carbon cycling across hierarchical levels. Plant Cell Environ. 44(7), 2402-2413.

Li, M., Yao, Y., Simmonds, I., Luo, D., Zhong, L., Chen, X., 2020d. Collaborative impact of the NAO and atmospheric blocking on European heatwaves, with a focus on the hot summer of 2018. Environ. Res. Lett. 15(11), 114003.

Li, P., Liu, Z., Zhou, X., Xie, B., Li, Z., Luo, Y., Zhu, Q., Peng, C., 2021b. Combined control of multiple extreme climate stressors on autumn vegetation phenology on the Tibetan Plateau under past and future climate change. Agric. For. Meteorol. 308-309, 108571.

Li, W., Jiang, Z., Li, L.Z.X., Luo, J.-J., Zhai, P., 2022c. Detection and attribution of changes in summer compound hot and dry events over northeastern china with cmip6 models. J. Meteorol. 36(1), 37-48.

Li, W., Zou, T., Li, L., Deng, Y., Sun, V.T., Zhang, Q., Layton, J.B., Setoguchi, S., 2019a. Impacts of the North Atlantic subtropical high on interannual variation of summertime heat stress over the conterminous United States. Clim. Dynam. 53(5), 3345-3359.

Li, X., You, Q., Ren, G., Wang, S., Zhang, Y., Yang, J., Zheng, G., 2018b. Concurrent droughts and hot extremes in northwest China from 1961 to 2017. Int. J. Climatol. 30(4), 2186– 2196.

Li, Y., Guan, K., Schnitkey, G.D., DeLucia, E., Peng, B., 2019b. Excessive rainfall leads to maize yield loss of a comparable magnitude to extreme drought in the United States. Global. Change. Biol. 25(7), 2325-2337.

Libonati, R., Geirinhas, J.L., Silva, P.S., Russo, A., Rodrigues, J.A., Belém, L.B.C., Nogueira, J., Roque, F.O., DaCamara, C.C., Nunes, A.M.B., Marengo, J.A., Trigo, R.M., 2022. Assessing the role of compound drought and heatwave events on unprecedented 2020 wildfires in the Pantanal. Environ. Res. Lett. 17(1), 015005.

Lim, E.-P., Hendon, H.H., Boschat, G., Hudson, D., Thompson, D.W.J., Dowdy, A.J., Arblaster, J.M., 2019. Australian hot and dry extremes induced by weakenings of the stratospheric polar vortex. Nat. Geosci. 12(11), 896-901.

Linscheid, N., Estupinan-Suarez, L.M., Brenning, A., Carvalhais, N., Cremer, F., Gans, F., Rammig, A., Reichstein, M., Sierra, C.A., Mahecha, M.D., 2020. Towards a global understanding of vegetation–climate dynamics at multiple timescales. Biogeosciences 17(4), 945-962.

Liu, W., Sun, F., Feng, Y., Li, C., Chen, J., Sang, Y.-F., Zhang, Q., 2021. Increasing population exposure to global warm-season concurrent dry and hot extremes under different warming levels. Environ. Res. Lett. 16(9), 094002.

Liu, X., He, B., Guo, L., Huang, L., Chen, D., 2020. Similarities and differences in the mechanisms causing the European summer heatwaves in 2003, 2010, and 2018. Earth's Future 8(4), e2019EF001386.

Liu, Z., Chen, X., Liu, F., Lin, K., He, Y., Cai, H., 2018. Joint dependence between river water temperature, air temperature, and discharge in the yangtze river: The role of the three gorges dam. J. Geophys. Res-Atmos. 123(21), 11,938-11,951.

Liu, Z., Zhou, W., 2021. The 2019 autumn hot drought over the middle-lower reaches of the Yangtze river in China: early propagation, process evolution, and concurrence. J. Geophys. Res-Atmos. 126(15), e2020JD033742.

Livneh, B., Hoerling, M.P., 2016. The physics of drought in the U.S. Central Great Plains. J. Climate 29(18), 6783-6804.

Lobell, D.B., Hammer, G.L., McLean, G., Messina, C., Roberts, M.J., Schlenker, W., 2013. The critical role of extreme heat for maize production in the United States. Nat. Clim. Change. 3(5), 497-501.

Lockart, N., Kavetski, D., Franks, S.W., 2009. On the recent warming in the Murray-Darling Basin: land surface interactions misunderstood. Geophys. Res. Lett. 36(24), L24405.

Long, B., Zhang, B., He, C., Shao, R., Tian, W., 2018. Is there a change from a warm-dry to a warm-wet climate in the Inland River Area of China? Interpretation and analysis through surface water balance. J. Geophys. Res-Atmos. 123(14), 7114– 7131.

Loughran, T.F., Pitman, A.J., Perkins-Kirkpatrick, S.E., 2019. The El Niño–Southern Oscillation’s effect on summer heatwave development mechanisms in Australia. Clim. Dynam. 52(9), 6279-6300.

Lu, Y., Hu, H., Li, C., Tian, F., 2018. Increasing compound events of extreme hot and dry days during growing seasons of wheat and maize in China. Sci. Rep. 8(1), 16700.

Luan, X., Bommarco, R., Scaini, A., Vico, G., 2021. Combined heat and drought suppress rainfed maize and soybean yields and modify irrigation benefits in the USA. Environ. Res. Lett. 16(6), 064023.

Luan, X., Vico, G., 2021. Canopy temperature and heat stress are increased by compound high air temperature and water stress, and reduced by irrigation – A modeling analysis. Hydrol. Earth Syst. Sci. 25(3), 1411-1423.

Luo, L., Apps, D., Arcand, S., Xu, H., Pan, M., Hoerling, M., 2017. Contribution of temperature and precipitation anomalies to the California drought during 2012–2015. Geophys. Res. Lett. 44(7), 3184-3192.

Luo, M., Ning, G., Xu, F., Wang, S., Liu, Z., Yang, Y., 2020. Observed heatwave changes in arid northwest China: physical mechanism and long-term trend. Atmos. Res. 242, 105009.

Lyon, B., 2009. Southern Africa summer drought and heat waves: observations and coupled model behavior. J. Climate 22(22), 6033-6046.

Madden, R.A., Williams, J., 1978. The correlation between temperature and precipitation in the United States and Europe. Mon. Wea. Rev. 106(1), 142-147.

Mahony, C.R., Cannon, A.J., 2018. Wetter summers can intensify departures from natural variability in a warming climate. Nat. Commun. 9(1), 783.

Mahrookashani, A., Siebert, S., Hüging, H., Ewert, F., 2017. Independent and combined effects of high temperature and drought stress around anthesis on wheat. J. Agron. Crop Sci. 203(6), 453-463.

Mahto, S.S., Mishra, V., 2020. Dominance of summer monsoon flash droughts in India. Environ. Res. Lett. 15(10), 104061.

Manning, C., Bevacqua, E., Widmann, M., Maraun, D., Van Loon, A.F., 2022. Large discrepancies in the representation of compound long-duration dry and hot spells over Europe in CMIP5. Weather Clim. Dynam. Discuss. 2022, 1-26.

Manning, C., Widmann, M., Bevacqua, E., Van Loon, A.F., Maraun, D., Vrac, M., 2018. Soil moisture drought in Europe: a compound event of precipitation and potential evapotranspiration on multiple time scales. J. Hydrometeorol. 19(8), 1255-1271.

Manning, C., Widmann, M., Bevacqua, E., Van Loon, A.F., Maraun, D., Vrac, M., 2019. Increased probability of compound long-duration dry and hot events in Europe during summer (1950–2013). Environ. Res. Lett. 14(9), 094006.

Marengo, J.A., Ambrizzi, T., Barreto, N., Cunha, A.P., Ramos, A.M., Skansi, M., Molina Carpio, J., Salinas, R., 2022. The heat wave of October 2020 in central South America. Int. J. Climatol. 42(4), 2281-2298.

Markonis, Y., Kumar, R., Hanel, M., Rakovec, O., Máca, P., AghaKouchak, A., 2021. The rise of compound warm-season droughts in Europe. Sci. Adv. 7(6), eabb9668.

Martin, J.-P., Germain, D., 2017. Large-scale teleconnection patterns and synoptic climatology of major snow-avalanche winters in the Presidential Range (New Hampshire, USA). Int. J. Climatol. 37(S1), 109-123.

Martin, J.T., Pederson, G.T., Woodhouse, C.A., Cook, E.R., McCabe, G.J., Anchukaitis, K.J., Wise, E.K., Erger, P.J., Dolan, L., McGuire, M., Gangopadhyay, S., Chase, K.J., Littell, J.S., Gray, S.T., St. George, S., Friedman, J.M., Sauchyn, D.J., St-Jacques, J.-M., King, J., 2020. Increased drought severity tracks warming in the United States' largest river basin. Proc. Natl. Acad. Sci. 117(21), 11328-11336.

Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M., 2021. Climate change 2021: the physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change, 2.

Mastrotheodoros, T., Pappas, C., Molnar, P., Burlando, P., Manoli, G., Parajka, J., Rigon, R., Szeles, B., Bottazzi, M., Hadjidoukas, P., Fatichi, S., 2020. More green and less blue water in the Alps during warmer summers. Nat. Clim. Change. 10(2), 155-161.

Matiu, M., Ankerst, D.P., Menzel, A., 2017. Interactions between temperature and drought in global and regional crop yield variability during 1961-2014. PLOS ONE 12(5), e0178339.

Matthews, T., Wilby, R.L., Murphy, C., 2019. An emerging tropical cyclone–deadly heat compound hazard. Nat. Clim. Change. 9(8), 602-606.

Mazdiyasni, O., AghaKouchak, A., 2015. Substantial increase in concurrent droughts and heatwaves in the United States. Proc. Natl. Acad. Sci. 112(37), 11484-11489.

McCabe, G.J., Wolock, D.M., Pederson, G.T., Woodhouse, C.A., McAfee, S., 2017. Evidence that recent warming is reducing upper Colorado River flows. Earth Interact. 21(10), 1-14.

McKinnon, K.A., Poppick, A., Simpson, I.R., 2021. Hot extremes have become drier in the United States Southwest. Nat. Clim. Change. 11, 598–604.

McPhillips, L.E., Chang, H., Chester, M.V., Depietri, Y., Friedman, E., Grimm, N.B., Kominoski, J.S., McPhearson, T., Méndez-Lázaro, P., Rosi, E.J., Shiva, J.S., 2018. Defining extreme events: a cross-disciplinary review. Earth's Future 6(3), 441–455.

Meehl, G.A., Richter, J.H., Teng, H., Capotondi, A., Cobb, K., Doblas-Reyes, F., Donat, M.G., England, M.H., Fyfe, J.C., Han, W., Kim, H., Kirtman, B.P., Kushnir, Y., Lovenduski, N.S., Mann, M.E., Merryfield, W.J., Nieves, V., Pegion, K., Rosenbloom, N., Sanchez, S.C., Scaife, A.A., Smith, D., Subramanian, A.C., Sun, L., Thompson, D., Ummenhofer, C.C., Xie, S.-P., 2021. Initialized earth system prediction from subseasonal to decadal timescales. Nat. Rev. Earth Environ. 2(5), 340-357.

Meng, Y., Hao, Z., Feng, S., Guo, Q., Zhang, Y., 2022a. Multivariate bias corrections of CMIP6 model simulations of compound dry and hot events across China. Environ. Res. Lett. in press.

Meng, Y., Hao, Z., Feng, S., Zhang, X., Hao, F., 2022b. Increase in compound dry-warm and wet-warm events under global warming in CMIP6 models. Glob. Planet. Change 210, 103773.

Merz, B., Kuhlicke, C., Kunz, M., Pittore, M., Babeyko, A., Bresch, D.N., Domeisen, D.I.V., Feser, F., Koszalka, I., Kreibich, H., Pantillon, F., Parolai, S., Pinto, J.G., Punge, H.J., Rivalta, E., Schröter, K., Strehlow, K., Weisse, R., Wurpts, A., 2020. Impact forecasting to support emergency management of natural hazards. Rev. Geophys. 58(4), e2020RG000704.

Messori, G., Bevacqua, E., Caballero, R., Coumou, D., De Luca, P., Faranda, D., Kornhuber, K., Martius, O., Pons, F., Raymond, C., Ye, K., Yiou, P., Zscheischler, J., 2021. Compound climate events and extremes in the midlatitudes: dynamics, simulation, and statistical characterization. Bull. Amer. Meteor. Soc 102(4), E774-E781.

Meyer, J., Kohn, I., Stahl, K., Hakala, K., Seibert, J., Cannon, A.J., 2019. Effects of univariate and multivariate bias correction on hydrological impact projections in alpine catchments. Hydrol. Earth Syst. Sci. 23(3), 1339-1354.

Milly, P.C.D., Dunne, K.A., 2020. Colorado River flow dwindles as warming-driven loss of reflective snow energizes evaporation. Science 367 (6483), 1252-1255.

Min, S.-K., Cai, W., Whetton, P., 2013. Influence of climate variability on seasonal extremes over Australia. J. Geophys. Res-Atmos. 118(2), 643-654.

Miralles, D.G., den Berg, M.J., Teuling, A.J., Jeu, R.A.M., 2012. Soil moisture-temperature coupling: a multiscale observational analysis. Geophys. Res. Lett. 39(21).

Miralles, D.G., Gentine, P., Seneviratne, S.I., Teuling, A.J., 2019. Land–atmospheric feedbacks during droughts and heatwaves: state of the science and current challenges. Ann. Ny. Acad. Sci. 1436 (1), 19-35.

Miralles, D.G., Teuling, A.J., van Heerwaarden, C.C., Vilà-Guerau de Arellano, J., 2014. Mega-heatwave temperatures due to combined soil desiccation and atmospheric heat accumulation. Nat. Geosci. 7, 345.

Mishra, A.K., Singh, V.P., 2010. A review of drought concepts. J. Hydrol. 391(1-2), 202-216.

Mishra, V., Aadhar, S., Mahto, S.S., 2021. Anthropogenic warming and intraseasonal summer monsoon variability amplify the risk of future flash droughts in India. npj Clim. Atmos. Sci. 4(1), 1.

Mishra, V., Thirumalai, K., Singh, D., Aadhar, S., 2020. Future exacerbation of hot and dry summer monsoon extremes in India. npj Clim. Atmos. Sci. 3(1), 10.

Mitchell, P.J., O'Grady, A.P., Hayes, K.R., Pinkard, E.A., 2014. Exposure of trees to drought-induced die-off is defined by a common climatic threshold across different vegetation types. Ecol. Evol. 4(7), 1088-1101.

Mittler, R., 2006. Abiotic stress, the field environment and stress combination. Trends Plant Sci. 11(1), 15-19.

Mo, K.C., Lettenmaier, D.P., 2020. Prediction of flash droughts over the United States. J. Hydrometeorol. 21(8), 1793-1810.

Morán-Tejeda, E., Herrera, S., López-Moreno, J.I., Revuelto, J., Lehmann, A., Beniston, M., 2013. Evolution and frequency (1970–2007) of combined temperature–precipitation modes in the Spanish mountains and sensitivity of snow cover. Reg. Environ. Change 13(4), 873-885.

Mu, M., De Kauwe, M.G., Ukkola, A.M., Pitman, A.J., Guo, W., Hobeichi, S., Briggs, P.R., 2021. Exploring how groundwater buffers the influence of heatwaves on vegetation function during multi-year droughts. Earth Syst. Dynam. 12(3), 919–938.

Mueller, B., Seneviratne, S.I., 2014. Systematic land climate and evapotranspiration biases in CMIP5 simulations. Geophys. Res. Lett. 41(1), 128-134.

Mukherjee, S., Ashfaq, M., Mishra, A.K., 2020. Compound drought and heatwaves at a global scale: the role of natural climate variability-associated synoptic patterns and land-surface energy budget anomalies. J. Geophys. Res-Atmos. 125(11), e2019JD031943.

Mukherjee, S., Mishra, A.K., 2021. Increase in compound drought and heatwaves in a warming world. Geophys. Res. Lett. 48(1), e2020GL090617.

Mukherjee, S., Mishra, A.K., 2022. Global flash drought analysis: uncertainties from indicators and datasets. Earth's Future 10(6), e2022EF002660.

Mukherjee, S., Mishra, A.K., Ashfaq, M., Kao, S.-C., 2022. Relative effect of anthropogenic warming and natural climate variability to changes in compound drought and heatwaves. J. Hydrol. 605, 127396.

Muthuvel, D., Mahesha, A., 2021. Spatiotemporal analysis of compound agrometeorological drought and hot events in India using a standardized index. J. Hydrol. Eng. 26(7), 04021022.

Nagavciuc, V., Scholz, P., Ionita, M., 2022. Hotspots for warm and dry summers in Romania. Nat. Hazards Earth Syst. Sci. 22(4), 1347-1369.

Nagler, T., Schepsmeier, U., Stoeber, J., Brechmann, E.C., Graeler, B., Erhardt, T., Almeida, C., Min, A., Czado, C., Hofmann, M., 2022. Statistical Inference of Vine Copulas. In: R. package (Editor).

NAS, 2016. Attribution of Extreme Weather Events in the Context of Climate Change. The National Academies Press, Washington, DC, 186 pp.

Naumann, G., Alfieri, L., Wyser, K., Mentaschi, L., Betts, R.A., Carrao, H., Spinoni, J., Vogt, J., Feyen, L., 2018. Global changes in drought conditions under different levels of warming. Geophys. Res. Lett. 45(7), 3285-3296.

Nelsen, R.B., 2006. An Introduction to Copulas. Springer, New York.

Nguyen, H., Wheeler, M.C., Hendon, H.H., Lim, E.-P., Otkin, J.A., 2021. The 2019 flash droughts in subtropical eastern Australia and their association with large-scale climate drivers. Weather Clim. Extrem. 32, 100321.

Nicholls, N., 2004. The changing nature of Australian droughts. Clim. Change 63(3), 323-336.

Nicolai-Shaw, N., Zscheischler, J., Hirschi, M., Gudmundsson, L., Seneviratne, S.I., 2017. A drought event composite analysis using satellite remote-sensing based soil moisture. Remote Sens. Environ. 203, 216-225.

Niggli, L., Huggel, C., Muccione, V., Neukom, R., Salzmann, N., 2022. Towards improved understanding of cascading and interconnected risks from concurrent weather extremes: analysis of historical heat and drought extreme events. PLOS Climate 1(8), e0000057.

Noguera, I., Vicente-Serrano, S.M., Domínguez-Castro, F., 2022. The rise of Atmospheric Evaporative Demand is increasing flash droughts in Spain during the warm season. Geophys. Res. Lett. 49(11), e2021GL097703.

O, S., Bastos, A., Reichstein, M., Li, W., Denissen, J., Graefen, H., Orth, R., 2022. The role of climate and vegetation in regulating drought–heat extremes. J. Climate 35(17), 5677-5685.

Obladen, N., Dechering, P., Skiadaresis, G., Tegel, W., Keßler, J., Höllerl, S., Kaps, S., Hertel, M., Dulamsuren, C., Seifert, T., Hirsch, M., Seim, A., 2021. Tree mortality of European beech and Norway spruce induced by 2018-2019 hot droughts in central Germany. Agric. For. Meteorol. 307, 108482.

Osman, M., Zaitchik, B.F., Winstead, N.S., 2022. Cascading drought-heat dynamics during the 2021 Southwest United States heatwave. Geophys. Res. Lett. 49(12), e2022GL099265.

Otero, N., Jurado, O.E., Butler, T., Rust, H.W., 2022. The impact of atmospheric blocking on the compounding effect of ozone pollution and temperature: a copula-based approach. Atmos. Chem. Phys. 22(3), 1905-1919.

Otto, F.E.L., 2017. Attribution of weather and climate events. Annu. Rev. Environ. Resour. 42(1), 627-646.

Overpeck, J.T., 2013. The challenge of hot drought. Nature 503(7476), 350-351.

Pan, S., Yang, J., Tian, H., Shi, H., Chang, J., Ciais, P., Francois, L., Frieler, K., Fu, B., Hickler, T., Ito, A., Nishina, K., Ostberg, S., Reyer, C.P.O., Schaphoff, S., Steinkamp, J., Zhao, F., 2020. Climate extreme versus carbon extreme: responses of terrestrial carbon fluxes to temperature and precipitation. J. Geophys. Res. Biogeosci. 125(4), e2019JG005252.

Papagiannopoulou, C., Miralles, D., Dorigo, W.A., Verhoest, N., Depoorter, M., Waegeman, W., 2017. Vegetation anomalies caused by antecedent precipitation in most of the world. Environ. Res. Lett. 12(7), 074016.

Perkins, S.E., 2015. A review on the scientific understanding of heatwaves—their measurement, driving mechanisms, and changes at the global scale. Atmos. Res. 164-165, 242-267.

Perkins, S.E., Alexander, L.V., Nairn, J.R., 2012. Increasing frequency, intensity and duration of observed global heatwaves and warm spells. Geophys. Res. Lett. 39(20), L20714

Pescaroli, G., Alexander, D., 2018. Understanding compound, interconnected, interacting, and cascading risks: a holistic framework. Risk Anal. 38(11), 2245-2257.

Pfleiderer, P., Jézéquel, A., Legrand, J., Legrix, N., Markantonis, I., Vignotto, E., Yiou, P., 2021. Simulating compound weather extremes responsible for critical crop failure with stochastic weather generators. Earth Syst. Dynam. 12(1), 103-120.

Pfleiderer, P., Schleussner, C.-F., Kornhuber, K., Coumou, D., 2019. Summer weather becomes more persistent in a 2 °C world. Nat. Clim. Change. 9(9), 666-671.

Piani, C., Haerter, J., 2012. Two dimensional bias correction of temperature and precipitation copulas in climate models. Geophys. Res. Lett. 39(20), L20401.

Potopová, V., Lhotka, O., Možný, M., Musiolková, M., 2020. Vulnerability of hop-yields due to compound drought and heat events over European key-hop regions. Int. J. Climatol. 41(S1), E2136– E2158.

Qin, P., Xu, H., Liu, M., Xiao, C., Forrest, K.E., Samuelsen, S., Tarroja, B., 2020. Assessing concurrent effects of climate change on hydropower supply, electricity demand, and greenhouse gas emissions in the Upper Yangtze River Basin of China. Appl. Energy 279, 115694.

Qing, Y., Wang, S., Ancell, B.C., Yang, Z.-L., 2022. Accelerating flash droughts induced by the joint influence of soil moisture depletion and atmospheric aridity. Nat. Commun. 13(1), 1139.

Quesada, B., Vautard, R., Yiou, P., Hirschi, M., Seneviratne, S.I., 2012. Asymmetric European summer heat predictability from wet and dry southern winters and springs. Nat. Clim. Change. 2(10), 736-741.

Röthlisberger, M., Frossard, L., Bosart, L.F., Keyser, D., Martius, O., 2019. Recurrent synoptic-scale rossby wave patterns and their effect on the persistence of cold and hot spells. J. Climate 32(11), 3207-3226.

Röthlisberger, M., Martius, O., 2019. Quantifying the local effect of northern hemisphere atmospheric blocks on the persistence of summer hot and dry spells. Geophys. Res. Lett. 46(16), 10101-10111.

Rammig, A., Wiedermann, M., Donges, J.F., Babst, F., Von Bloh, W., Frank, D., Thonicke, K., Mahecha, M.D., 2015. Coincidences of climate extremes and anomalous vegetation responses: comparing tree ring patterns to simulated productivity. Biogeosciences 12(2), 373-385.

Rana, A., Moradkhani, H., Qin, Y., 2017. Understanding the joint behavior of temperature and precipitation for climate change impact studies. Theor. Appl. Climatol. 129(1), 321-339.

Ray, D.K., Gerber, J.S., MacDonald, G.K., West, P.C., 2015. Climate variation explains a third of global crop yield variability. Nat. Commun. 6, 5989.

Raymond, C., Horton, R.M., Zscheischler, J., Martius, O., AghaKouchak, A., Balch, J., Bowen, S.G., Camargo, S.J., Hess, J., Kornhuber, K., Oppenheimer, M., Ruane, A.C., Wahl, T., White, K., 2020a. Understanding and managing connected extreme events. Nat. Clim. Change. 10, 611–621.

Raymond, C., Matthews, T., Horton, R.M., 2020b. The emergence of heat and humidity too severe for human tolerance. Sci. Adv. 6(19), eaaw1838.

Raymond, C., Suarez-Gutierrez, L., Kornhuber, K., Pascolini-Campbell, M., Sillmann, J., Waliser, D.E., 2022. Increasing spatiotemporal proximity of heat and precipitation extremes in a warming world quantified by a large model ensemble. Environ. Res. Lett. 17(3), 035005.

Reddy, P.J., Perkins-Kirkpatrick, S.E., Ridder, N.N., Sharples, J.J., 2022. Combined role of ENSO and IOD on compound drought and heatwaves in Australia using two CMIP6 large ensembles. Weather Clim. Extrem. 37, 100469.

Rehfeld, K., Laepple, T., 2016. Warmer and wetter or warmer and dryer? Observed versus simulated covariability of Holocene temperature and rainfall in Asia. Earth. Planet. Sc. Lett 436, 1-9.

Reichstein, M., Ciais, P., Papale, D., Valentini, R., Running, S., Viovy, N., Cramer, W., Granier, A., OgÉE, J., Allard, V., Aubinet, M., Bernhofer, C., Buchmann, N., Carrara, A., GrÜNwald, T., Heimann, M., Heinesch, B., Knohl, A., Kutsch, W., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourcival, J.M., Pilegaard, K., Pumpanen, J., Rambal, S., Schaphoff, S., Seufert, G., Soussana, J.F., Sanz, M.J., Vesala, T., Zhao, M., 2007. Reduction of ecosystem productivity and respiration during the European summer 2003 climate anomaly: a joint flux tower, remote sensing and modelling analysis. Global. Change. Biol. 13(3), 634-651.

Ribeiro, A.F.S., Brando, P.M., Santos, L., Rattis, L., Hirschi, M., Hauser, M., Seneviratne, S.I., Zscheischler, J., 2022. A compound event-oriented framework to tropical fire risk assessment in a changing climate. Environ. Res. Lett. 17(6), 065015.

Ribeiro, A.F.S., Russo, A., Gouveia, C.M., Páscoa, P., Pires, C.A.L., 2019. Probabilistic modelling of the dependence between rainfed crops and drought hazard. Nat. Hazards Earth Syst. Sci. 19(12), 2795-2809.

Ribeiro, A.F.S., Russo, A., Gouveia, C.M., Páscoa, P., Zscheischler, J., 2020a. Risk of crop failure due to compound dry and hot extremes estimated with nested copulas. Biogeosciences 17(19), 4815–4830.

Ribeiro, A.F.S., Russo, A., Gouveia, C.M., Pires, C.A.L., 2020b. Drought-related hot summers: a joint probability analysis in the Iberian Peninsula. Weather Clim. Extrem. 30, 100279.

Ridder, N.N., Pitman, A.J., Ukkola, A.M., 2021. Do CMIP6 climate models simulate global or regional compound events skillfully? Geophys. Res. Lett. 48(2), e2020GL091152.

Ridder, N.N., Pitman, A.J., Ukkola, A.M., 2022a. High impact compound events in Australia. Weather Clim. Extrem. 36, 100457.

Ridder, N.N., Pitman, A.J., Westra, S., Ukkola, A., Hong, X.D., Bador, M., Hirsch, A.L., Evans, J.P., Di Luca, A., Zscheischler, J., 2020. Global hotspots for the occurrence of compound events. Nat. Commun. 11(1), 5956.

Ridder, N.N., Ukkola, A.M., Pitman, A.J., Perkins-Kirkpatrick, S.E., 2022b. Increased occurrence of high impact compound events under climate change. npj Clim. Atmos. Sci. 5(1), 3.

Rizhsky, L., Liang, H., Mittler, R., 2002. The combined effect of drought stress and heat shock on gene expression in tobacco. Plant Physiol. 130(3), 1143-1151.

Rodrigo, F.S., 2015. On the covariability of seasonal temperature and precipitation in Spain, 1956–2005. Int. J. Climatol. 35(11), 3362-3370.

Rodrigo, F.S., 2021. Exploring combined influences of seasonal East Atlantic (EA) and North Atlantic Oscillation (NAO) on the temperature-precipitation relationship in the Iberian Peninsula. Geosciences 11(5), 211.

Rogers, C.D.W., Ting, M., Li, C., Kornhuber, K., Coffel, E.D., Horton, R.M., Raymond, C., Singh, D., 2021. Recent increases in exposure to extreme humid-heat events disproportionately affect populated regions. Geophys. Res. Lett. 48(19), e2021GL094183.

Ruffault, J., Curt, T., Moron, V., Trigo, R.M., Mouillot, F., Koutsias, N., Pimont, F., Martin-StPaul, N., Barbero, R., Dupuy, J.-L., Russo, A., Belhadj-Khedher, C., 2020. Increased likelihood of heat-induced large wildfires in the Mediterranean Basin. Sci. Rep. 10(1), 13790.

Rummukainen, M., 2012. Changes in climate and weather extremes in the 21st century. Wiley Interdiscip. Rev. Clim. Change 3(2), 115–129.

Russo, A., Gouveia, C.M., Dutra, E., Soares, P.M.M., Trigo, R.M., 2019. The synergy between drought and extremely hot summers in the Mediterranean. Environ. Res. Lett. 14(1), 014011.

Russo, A., Gouveia, C.M., Páscoa, P., DaCamara, C.C., Sousa, P.M., Trigo, R.M., 2017. Assessing the role of drought events on wildfires in the Iberian Peninsula. Agric. For. Meteorol. 237-238, 50-59.

Sadegh, M., Moftakhari, H., Gupta, H.V., Ragno, E., Mazdiyasni, O., Sanders, B., Matthew, R., AghaKouchak, A., 2018. Multihazard scenarios for analysis of compound extreme events. Geophys. Res. Lett. 45(11), 5470-5480.

Santanello, J.A., Dirmeyer, P.A., Ferguson, C.R., Findell, K.L., Tawfik, A.B., Berg, A., Ek, M., Gentine, P., Guillod, B.P., van Heerwaarden, C., Roundy, J., Wulfmeyer, V., 2018. Land–atmosphere interactions: the loco perspective. Bull. Amer. Meteor. Soc 99(6), 1253-1272.

Sarhadi, A., Ausín, M.C., Wiper, M.P., Touma, D., Diffenbaugh, N.S., 2018. Multidimensional risk in a nonstationary climate: joint probability of increasingly severe warm and dry conditions. Sci. Adv. 4(11), eaau3487.

Sarojini, B.B., Stott, P.A., Black, E., 2016. Detection and attribution of human influence on regional precipitation. Nat. Clim. Change. 6(7), 669-675.

Scaife, A.A., Woollings, T., Knight, J., Martin, G., Hinton, T., 2010. Atmospheric blocking and mean biases in climate models. J. Climate 23(23), 6143-6152.

Schauberger, B., Archontoulis, S., Arneth, A., Balkovic, J., Ciais, P., Deryng, D., Elliott, J., Folberth, C., Khabarov, N., Müller, C., Pugh, T.A.M., Rolinski, S., Schaphoff, S., Schmid, E., Wang, X., Schlenker, W., Frieler, K., 2017. Consistent negative response of US crops to high temperatures in observations and crop models. Nat. Commun. 8(1), 13931.

Schauberger, B., Makowski, D., Ben-Ari, T., Boé, J., Ciais, P., 2021. No historical evidence for increased vulnerability of French crop production to climatic hazards. Agric. For. Meteorol. 306, 108453.

Schauwecker, S., Gascón, E., Park, S., Ruiz-Villanueva, V., Schwarb, M., Sempere-Torres, D., Stoffel, M., Vitolo, C., Rohrer, M., 2019. Anticipating cascading effects of extreme precipitation with pathway schemes - three case studies from Europe. Environ. Int. 127, 291-304.

Schewe, J., Gosling, S.N., Reyer, C., Zhao, F., Ciais, P., Elliott, J., Francois, L., Huber, V., Lotze, H.K., Seneviratne, S.I., van Vliet, M.T.H., Vautard, R., Wada, Y., Breuer, L., Büchner, M., Carozza, D.A., Chang, J., Coll, M., Deryng, D., de Wit, A., Eddy, T.D., Folberth, C., Frieler, K., Friend, A.D., Gerten, D., Gudmundsson, L., Hanasaki, N., Ito, A., Khabarov, N., Kim, H., Lawrence, P., Morfopoulos, C., Müller, C., Müller Schmied, H., Orth, R., Ostberg, S., Pokhrel, Y., Pugh, T.A.M., Sakurai, G., Satoh, Y., Schmid, E., Stacke, T., Steenbeek, J., Steinkamp, J., Tang, Q., Tian, H., Tittensor, D.P., Volkholz, J., Wang, X., Warszawski, L., 2019. State-of-the-art global models underestimate impacts from climate extremes. Nat. Commun. 10(1), 1005.

Schlenker, W., Roberts, M.J., 2009. Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. Proc. Natl. Acad. Sci. 106(37), 15594-15598.

Schoelzel, C., Friederichs, P., 2008. Multivariate non-normally distributed random variables in climate research–introduction to the copula approach. Nonlinear Processes Geophys. 15(5), 761-772.

Schubert, S.D., Stewart, R.E., Wang, H., Barlow, M., Berbery, E.H., Cai, W., Hoerling, M.P., Kanikicharla, K.K., Koster, R.D., Lyon, B., 2016. Global meteorological drought: A synthesis of current understanding with a focus on SST drivers of precipitation deficits. J. Climate 29(11), 3989-4019.

Schubert, S.D., Wang, H., Koster, R.D., Suarez, M.J., Groisman, P.Y., 2014. Northern Eurasian heat waves and droughts. J. Climate 27(9), 3169-3207.

Schumacher, D.L., Keune, J., Dirmeyer, P., Miralles, D.G., 2022. Drought self-propagation in drylands due to land–atmosphere feedbacks. Nat. Geosci. 15(4), 262-268.

Schumacher, D.L., Keune, J., van Heerwaarden, C.C., Vilà-Guerau de Arellano, J., Teuling, A.J., Miralles, D.G., 2019. Amplification of mega-heatwaves through heat torrents fuelled by upwind drought. Nat. Geosci. 12(9), 712-717.

Seager, R., Hoerling, M., 2014. Atmosphere and ocean origins of North American droughts. J. Climate 27(12), 4581-4606.

Seager, R., Hoerling, M., Schubert, S., Wang, H., Lyon, B., Kumar, A., Nakamura, J., Henderson, N., 2015. Causes of the 2011–14 California drought. J. Climate 28(18), 6997-7024.

Sedlmeier, K., Feldmann, H., Schädler, G., 2018. Compound summer temperature and precipitation extremes over central Europe. Theor. Appl. Climatol. 131(3), 1493-1501.

Seneviratne, S.I., Corti, T., Davin, E.L., Hirschi, M., Jaeger, E.B., Lehner, I., Orlowsky, B., Teuling, A.J., 2010. Investigating soil moisture–climate interactions in a changing climate: a review. Earth Sci. Rev. 99(3-4), 125-161.

Seneviratne, S.I., Nicholls, N., Easterling, D., Goodess, C.M., Kanae, S., Kossin, J., Luo, Y., Marengo, J., McInnes, K., Rahimi, M., 2012. Changes in climate extremes and their impacts on the natural physical environment. In: Field CB, Barros V, Stocker TF, Qin D, Dokken D, Ebi KL, Mastrandrea MD, Mach KJ, Plattner G-K, Allen SK, et al, eds. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation.A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC) Cambridge University Press, Cambridge, UK, pp. 109–230.

Seneviratne, S.I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Di Luca, A., Vicente-Serrano, S.M., Wehner, M., Zhou, B., 2021. Weather and climate extreme events in a changing climate. In: V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (Editors), Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, United Kingdom and New York, NY, USA, pp. 1513-1766.

Seo, Y.-W., Ha, K.-J., Park, T.-W., 2021. Feedback attribution to dry heatwaves over East Asia. Environ. Res. Lett. 16(6), 064003.

Serinaldi, F., 2016. Can we tell more than we can know? The limits of bivariate drought analyses in the United States. Stoch. Environ. Res. Risk Assess. 30(6), 1691-1704.

Sharma, S., Mujumdar, P., 2017. Increasing frequency and spatial extent of concurrent meteorological droughts and heatwaves in India. Sci. Rep. 7(1), 15582.

Sharma, S., Mujumdar, P.P., 2022. Modeling concurrent hydroclimatic extremes with parametric multivariate extreme value models. Water Resour. Res. 58(2), e2021WR031519.

Sheffield, J., Wood, E.F., Roderick, M.L., 2012. Little change in global drought over the past 60 years. Nature 491, 435–438

Shepherd, T.G., Boyd, E., Calel, R.A., Chapman, S.C., Dessai, S., Dima-West, I.M., Fowler, H.J., James, R., Maraun, D., Martius, O., Senior, C.A., Sobel, A.H., Stainforth, D.A., Tett, S.F.B., Trenberth, K.E., van den Hurk, B.J.J.M., Watkins, N.W., Wilby, R.L., Zenghelis, D.A., 2018. Storylines: an alternative approach to representing uncertainty in physical aspects of climate change. Clim. Change 151(3), 555-571.

Shi, Z., Jia, G., Zhou, Y., Xu, X., Jiang, Y., 2021. Amplified intensity and duration of heatwaves by concurrent droughts in China. Atmos. Res. 261, 105743.

Siebert, S., Webber, H., Zhao, G., Ewert, F., 2017. Heat stress is overestimated in climate impact studies for irrigated agriculture. Environ. Res. Lett. 12(5), 054023.

Sillmann, J., Shepherd, T.G., van den Hurk, B., Hazeleger, W., Martius, O., Slingo, J., Zscheischler, J., 2021. Event-based storylines to address climate risk. Earth's Future 9(2), e2020EF001783.

Sillmann, J., Thorarinsdottir, T., Keenlyside, N., Schaller, N., Alexander, L.V., Hegerl, G., Seneviratne, S.I., Vautard, R., Zhang, X., Zwiers, F.W., 2017. Understanding, modeling and predicting weather and climate extremes: challenges and opportunities. Weather Clim. Extrem. 18, 65-74.

Singh, H., Najafi, M.R., Cannon, A.J., 2021. Characterizing non-stationary compound extreme events in a changing climate based on large-ensemble climate simulations. Clim. Dynam. 56(5), 1389-1405.

Singh, H., Pirani, F.J., Najafi, M.R., 2020. Characterizing the temperature and precipitation covariability over Canada. Theor. Appl. Climatol. 139(3), 1543-1558.

Singh, H., Reza Najafi, M., 2020. Evaluation of gridded climate datasets over Canada using univariate and bivariate approaches: implications for hydrological modelling. J. Hydrol. 584, 124673.

Sippel, S., Otto, F.E.L., Forkel, M., Allen, M.R., Guillod, B.P., Heimann, M., Reichstein, M., Seneviratne, S.I., Thonicke, K., Mahecha, M.D., 2016a. A novel bias correction methodology for climate impact simulations. Earth Syst. Dynam. 7(1), 71-88.

Sippel, S., Reichstein, M., Ma, X., Mahecha, M.D., Lange, H., Flach, M., Frank, D., 2018. Drought, heat, and the carbon cycle: a review. Curr. Clim. Change Rep. 4(3), 266-286.

Sippel, S., Zscheischler, J., Mahecha, M.D., Orth, R., Reichstein, M., Vogel, M., Seneviratne, S.I., 2017. Refining multi-model projections of temperature extremes by evaluation against land–atmosphere coupling diagnostics. Earth Syst. Dynam. 8(2), 387-403.

Sippel, S., Zscheischler, J., Reichstein, M., 2016b. Ecosystem impacts of climate extremes crucially depend on the timing. Proc. Natl. Acad. Sci. 113(21), 5768-5770.

Slater, L.J., Anderson, B., Buechel, M., Dadson, S., Han, S., Harrigan, S., Kelder, T., Kowal, K., Lees, T., Matthews, T., Murphy, C., Wilby, R.L., 2021. Nonstationary weather and water extremes: a review of methods for their detection, attribution, and management. Hydrol. Earth Syst. Sci. 25(7), 3897–3935.

Slosson, J.R., Kelleher, C., Hoke, G.D., 2021. Contrasting impacts of a hotter and drier future on streamflow and catchment scale sediment flux in the high andes. J. Geophys. Res. Earth. Surf. 126(8), e2021JF006182.

Sousa, P.M., Barriopedro, D., García-Herrera, R., Ordóñez, C., Soares, P.M.M., Trigo, R.M., 2020. Distinct influences of large-scale circulation and regional feedbacks in two exceptional 2019 European heatwaves. Commun. Earth Environ. 1(1), 48.

Sousa, P.M., Blamey, R.C., Reason, C.J.C., Ramos, A.M., Trigo, R.M., 2018. The 'Day Zero' Cape Town drought and the poleward migration of moisture corridors. Environ. Res. Lett. 13(12), 124025.

Squire, D.T., Richardson, D., Risbey, J.S., Black, A.S., Kitsios, V., Matear, R.J., Monselesan, D., Moore, T.S., Tozer, C.R., 2021. Likelihood of unprecedented drought and fire weather during Australia's 2019 megafires. npj Clim. Atmos. Sci. 4(1), 64.

Stocker, B.D., Zscheischler, J., Keenan, T.F., Prentice, I.C., Seneviratne, S.I., Peñuelas, J., 2019. Drought impacts on terrestrial primary production underestimated by satellite monitoring. Nat. Geosci. 12(4), 264-270.

Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M., 2013. Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change 1535.

Stott, P.A., Christidis, N., Otto, F.E., Sun, Y., Vanderlinden, J.P., van Oldenborgh, G.J., Vautard, R., von Storch, H., Walton, P., Yiou, P., 2016. Attribution of extreme weather and climate-related events. Wiley Interdiscip. Rev. Clim. Change 7(1), 23-41.

Su, H., Dickinson, R.E., 2017. On the spatial gradient of soil moisture-precipitation feedback strength in the 2011 April drought in the Southern Great Plains. J. Climate 30, 829–848.

Sun, C.X., Huang, G.H., Fan, Y., Zhou, X., Lu, C., Wang, X.Q., 2019. Drought occurring with hot extremes: changes under future climate change on Loess Plateau, China. Earth's Future 7(6), 587-604.

Sun, Q., Miao, C., AghaKouchak, A., Duan, Q., 2017. Unraveling anthropogenic influence on the changing risk of heat waves in China. Geophys. Res. Lett. 44(10), 5078-5085.

Sun, Y., Zhang, X., Ding, Y., Chen, D., Qin, D., Zhai, P., 2022. Understanding human influence on climate change in China. Natl. Sci. Rev. 9(3), nwab113.

Sutanto, S.J., Vitolo, C., Di Napoli, C., D'Andrea, M., Van Lanen, H.A.J., 2020. Heatwaves, droughts, and fires: Exploring compound and cascading dry hazards at the pan-European scale. Environ. Int. 134, 105276.

Suzuki, N., Rivero, R.M., Shulaev, V., Blumwald, E., Mittler, R., 2014. Abiotic and biotic stress combinations. New Phytol. 203(1), 32-43.

Tang, Z., Yang, T., Lin, X., Li, X., Cao, R., Li, W., 2022. Future changes in the risk of compound hot and dry events over China estimated with two large ensembles. Plos one 17(3), e0264980.

Tavakol, A., Rahmani, V., Harrington, J., 2020a. Temporal and spatial variations in the frequency of compound hot, dry, and windy events in the central United States. Sci. Rep. 10(1), 15691.

Tavakol, A., Rahmani, V., Harrington Jr, J., 2020b. Probability of compound climate extremes in a changing climate: A copula-based study of hot, dry, and windy events in the central United States. Environ. Res. Lett. 15(10), 104058.

Taylor, K.E., Stouffer, R.J., Meehl, G.A., 2012. An overview of CMIP5 and the experiment design. Bull. Amer. Meteor. Soc 93(4), 485-498.

Tencer, B., Bettolli, M.L., Rusticucci, M., 2016. Compound temperature and precipitation extreme events in southern South America: associated atmospheric circulation, and simulations by a multi-RCM ensemble. Climate Res. 68(2-3), 183-199.

Teuling, A.J., 2018. A hot future for European droughts. Nat. Clim. Change. 8(5), 364.

Teuling, A.J., Van Loon, A.F., Seneviratne, S.I., Lehner, I., Aubinet, M., Heinesch, B., Bernhofer, C., Grünwald, T., Prasse, H., Spank, U., 2013. Evapotranspiration amplifies European summer drought. Geophys. Res. Lett. 40(10), 2071-2075.

Thiery, W., Visser, A.J., Fischer, E.M., Hauser, M., Hirsch, A.L., Lawrence, D.M., Lejeune, Q., Davin, E.L., Seneviratne, S.I., 2020. Warming of hot extremes alleviated by expanding irrigation. Nat. Commun. 11(1), 290.

Tian, F., Klingaman, N.P., Dong, B., 2021. The driving processes of concurrent hot and dry extreme events in china. J. Climate 34(5), 1809-1824.

Tilloy, A., Malamud, B., Joly-Laugel, A., 2021. A methodology for the spatiotemporal identification of compound hazards: Wind and precipitation extremes in great britain (1979–2019). Earth Syst. Dynam. 13(2), 993–1020.

Tilloy, A., Malamud, B.D., Winter, H., Joly-Laugel, A., 2019. A review of quantification methodologies for multi-hazard interrelationships. Earth Sci. Rev. 196, 102881.

Tilloy, A., Malamud, B.D., Winter, H., Joly-Laugel, A., 2020. Evaluating the efficacy of bivariate extreme modelling approaches for multi-hazard scenarios. Nat. Hazards Earth Syst. Sci. 20(8), 2091-2117.

Tootoonchi, F., Sadegh, M., Haerter, J.O., Räty, O., Grabs, T., Teutschbein, C., 2022. Copulas for hydroclimatic analysis: a practice-oriented overview. WIREs Water 9(2), e1579.

Toreti, A., Cronie, O., Zampieri, M., 2019. Concurrent climate extremes in the key wheat producing regions of the world. Sci. Rep. 9(1), 5493.

Trenberth, K.E., Dai, A., van der Schrier, G., Jones, P.D., Barichivich, J., Briffa, K.R., Sheffield, J., 2014. Global warming and changes in drought. Nat. Clim. Change. 4(1), 17-22.

Trenberth, K.E., Shea, D.J., 2005. Relationships between precipitation and surface temperature. Geophys. Res. Lett 32(14), L14703.

Troy, T.J., Kipgen, C., Pal, I., 2015. The impact of climate extremes and irrigation on US crop yields. Environ. Res. Lett. 10(5), 054013.

Tschumi, E., Lienert, S., van der Wiel, K., Joos, F., Zscheischler, J., 2022a. A climate database with varying drought-heat signatures for climate impact modelling. Geosci. Data J. 9(1), 154-166.

Tschumi, E., Lienert, S., van der Wiel, K., Joos, F., Zscheischler, J., 2022b. The effects of varying drought-heat signatures on terrestrial carbon dynamics and vegetation composition. Biogeosciences. 19(7), 1979–1993.

Tschumi, E., Zscheischler, J., 2019. Countrywide climate features during recorded climate-related disasters. Clim. Change 158, 593–609.

Turner, S.W.D., Voisin, N., Fazio, J., Hua, D., Jourabchi, M., 2019. Compound climate events transform electrical power shortfall risk in the Pacific Northwest. Nat. Commun. 10(1), 8.

Udall, B., Overpeck, J., 2017. The twenty-first century Colorado River hot drought and implications for the future. Water Resour. Res. 53(3), 2404-2418.

Ukkola, A.M., De Kauwe, M.G., Pitman, A.J., Best, M.J., Abramowitz, G., Haverd, V., Decker, M., Haughton, N., 2016. Land surface models systematically overestimate the intensity, duration and magnitude of seasonal-scale evaporative droughts. Environ. Res. Lett. 11(10), 104012.

Ukkola, A.M., Pitman, A.J., Donat, M.G., De Kauwe, M.G., Angélil, O., 2018. Evaluating the Contribution of Land-Atmosphere Coupling to Heat Extremes in CMIP5 Models. Geophys. Res. Lett. 45(17), 9003-9012.

Van de Velde, J., Demuzere, M., De Baets, B., Verhoest, N.E.C., 2022. Impact of bias nonstationarity on the performance of uni- and multivariate bias-adjusting methods: a case study on data from Uccle, Belgium. Hydrol. Earth Syst. Sci. 26, 2319–2344.

van der Molen, M.K., Dolman, A.J., Ciais, P., Eglin, T., Gobron, N., Law, B.E., Meir, P., Peters, W., Phillips, O.L., Reichstein, M., Chen, T., Dekker, S.C., Doubková, M., Friedl, M.A., Jung, M., van den Hurk, B.J.J.M., de Jeu, R.A.M., Kruijt, B., Ohta, T., Rebel, K.T., Plummer, S., Seneviratne, S.I., Sitch, S., Teuling, A.J., van der Werf, G.R., Wang, G., 2011. Drought and ecosystem carbon cycling. Agric. For. Meteorol. 151(7), 765-773.

van der Wiel, K., Selten, F.M., Bintanja, R., Blackport, R., Screen, J.A., 2020. Ensemble climate-impact modelling: extreme impacts from moderate meteorological conditions. Environ. Res. Lett. 15(3), 034050.

Van Tiel, M., Van Loon, A.F., Seibert, J., Stahl, K., 2021. Hydrological response to warm and dry weather: do glaciers compensate? Hydrol. Earth Syst. Sci. 25(6), 3245-3265.

van Vliet, M.T.H., Sheffield, J., Wiberg, D., Wood, E.F., 2016. Impacts of recent drought and warm years on water resources and electricity supply worldwide. Environ. Res. Lett. 11(12), 124021.

Vicente-Serrano, S.M., McVicar, T.R., Miralles, D.G., Yang, Y., Tomas-Burguera, M., 2020a. Unraveling the influence of atmospheric evaporative demand on drought and its response to climate change. WIREs Clim. Change 11(2), e632.

Vicente-Serrano, S.M., Miralles, D.G., McDowell, N., Brodribb, T., Domínguez-Castro, F., Leung, R., Koppa, A., 2022. The uncertain role of rising atmospheric CO2 on global plant transpiration. Earth Sci. Rev. 230, 104055.

Vicente-Serrano, S.M., Quiring, S.M., Peña-Gallardo, M., Yuan, S., Domínguez-Castro, F., 2020b. A review of environmental droughts: increased risk under global warming? Earth Sci. Rev. 201, 102953.

Villalobos-Herrera, R., Bevacqua, E., Ribeiro, A.F.S., Auld, G., Crocetti, L., Mircheva, B., Ha, M., Zscheischler, J., De Michele, C., 2021. Towards a compound-event-oriented climate model evaluation: a decomposition of the underlying biases in multivariate fire and heat stress hazards. Nat. Hazards Earth Syst. Sci. 21(6), 1867–1885.

Visser-Quinn, A., Beevers, L., Collet, L., Formetta, G., Smith, K., Wanders, N., Thober, S., Pan, M., Kumar, R., 2019. Spatio-temporal analysis of compound hydro-hazard extremes across the UK. Adv. Water Resour. 130, 77-90.

Vitolo, C., Di Napoli, C., Di Giuseppe, F., Cloke, H.L., Pappenberger, F., 2019. Mapping combined wildfire and heat stress hazards to improve evidence-based decision making. Environ. Int. 127, 21-34.

Vogel, J., Paton, E., Aich, V., Bronstert, A., 2021a. Increasing compound warm spells and droughts in the Mediterranean Basin. Weather Clim. Extrem. 32, 100312.

Vogel, J., Rivoire, P., Deidda, C., Rahimi, L., Sauter, C.A., Tschumi, E., van der Wiel, K., Zhang, T., Zscheischler, J., 2021b. Identifying meteorological drivers of extreme impacts: an application to simulated crop yields. Earth Syst. Dynam. 12(1), 151-172.

Vogel, M.M., Hauser, M., Seneviratne, S.I., 2020. Projected changes in hot, dry and wet extreme events' clusters in CMIP6 multi-model ensemble. Environ. Res. Lett. 15(9), 094021.

Vogel, M.M., Zscheischler, J., Seneviratne, S.I., 2018. Varying soil moisture–atmosphere feedbacks explain divergent temperature extremes and precipitation projections in central Europe. Earth Syst. Dynam. 9(3), 1107-1125.

Vogel, M.M., Zscheischler, J., Wartenburger, R., Dee, D., Seneviratne, S.I., 2019. Concurrent 2018 hot extremes across Northern Hemisphere due to human-induced climate change. Earth's Future 7(7), 692–703.

von Buttlar, J., Zscheischler, J., Rammig, A., Sippel, S., Reichstein, M., Knohl, A., Jung, M., Menzer, O., Arain, M.A., Buchmann, N., Cescatti, A., Gianelle, D., Kiely, G., Law, B.E., Magliulo, V., Margolis, H., McCaughey, H., Merbold, L., Migliavacca, M., Montagnani, L., Oechel, W., Pavelka, M., Peichl, M., Rambal, S., Raschi, A., Scott, R.L., Vaccari, F.P., van Gorsel, E., Varlagin, A., Wohlfahrt, G., Mahecha, M.D., 2018. Impacts of droughts and extreme-temperature events on gross primary production and ecosystem respiration: a systematic assessment across ecosystems and climate zones. Biogeosciences 15(5), 1293-1318.

Vrac, M., Friederichs, P., 2015. Multivariate-intervariable, spatial, and temporal-bias correction. J. Climate 28(1), 218-237.

Vrac, M., Thao, S., Yiou, P., 2022. Should multivariate bias corrections of climate simulations account for changes of rank correlation over time? J. Geophys. Res-Atmos. 127(14), e2022JD036562.

Wang, H., Schubert, S., Koster, R., Ham, Y.G., Suarez, M., 2014. On the role of SST forcing in the 2011 and 2012 extreme U.S. heat and drought: a study in contrasts. J. Hydrometeorol. 15(3), 1255-1273.

Wang, J., Chen, Y., Liao, W., He, G., Tett, S.F.B., Yan, Z., Zhai, P., Feng, J., Ma, W., Huang, C., Hu, Y., 2021a. Anthropogenic emissions and urbanization increase risk of compound hot extremes in cities. Nat. Clim. Change. 11, 1084–1089.

Wang, J., Chen, Y., Tett, S.F.B., Yan, Z., Zhai, P., Feng, J., Xia, J., 2020a. Anthropogenically-driven increases in the risks of summertime compound hot extremes. Nat. Commun. 11(1), 528.

Wang, L., Liu, H., Chen, D., Zhang, P., Leavitt, S., Liu, Y., Fang, C., Sun, C., Cai, Q., Gui, Z., Liang, B., Shi, L., Liu, F., Zheng, Y., Grießinger, J., 2022. The 1820s Marks a Shift to Hotter-Drier Summers in Western Europe Since 1360. Geophys. Res. Lett. 49(15), e2022GL099692.

Wang, P., Zhang, Q., Yang, Y., Tang, J., 2019a. The sensitivity to initial soil moisture for three severe cases of heat waves over eastern China. Front. Environ. Sci. 7, 18.

Wang, R., Lü, G., Ning, L., Yuan, L., Li, L., 2021b. Likelihood of compound dry and hot extremes increased with stronger dependence during warm seasons. Atmos. Res. 260, 105692.

Wang, S., Huang, J., Yuan, X., 2021c. Attribution of 2019 extreme spring–early summer hot drought over Yunnan in southwestern China. Bull. Amer. Meteor. Soc 102(1), S91-S96.

Wang, S., Zhang, Y., Ju, W., Porcar-Castell, A., Ye, S., Zhang, Z., Brümmer, C., Urbaniak, M., Mammarella, I., Juszczak, R., Folkert Boersma, K., 2020b. Warmer spring alleviated the impacts of 2018 European summer heatwave and drought on vegetation photosynthesis. Agric. For. Meteorol. 295, 108195.

Wang, S.S.-Y., Kim, H., Coumou, D., Yoon, J.-H., Zhao, L., Gillies, R.R., 2019b. Consecutive extreme flooding and heat wave in Japan: Are they becoming a norm? Atmos Sci. Lett. 20(10), e933.

Wang, X., Qiu, B., Li, W., Zhang, Q., 2019c. Impacts of drought and heatwave on the terrestrial ecosystem in China as revealed by satellite solar-induced chlorophyll fluorescence. Sci. Total. Environ. 693, 133627.

Ward, P.J., Daniell, J., Duncan, M., Dunne, A., Hananel, C., Hochrainer-Stigler, S., Tijssen, A., Torresan, S., Ciurean, R., Gill, J., 2022. Invited perspectives: a research agenda towards disaster risk management pathways in multi-(hazard-) risk assessment. Natural Hazards and Earth System Science 22(4), 1487-1497.

Watts, N., Adger, W.N., Agnolucci, P., Blackstock, J., Byass, P., Cai, W., Chaytor, S., Colbourn, T., Collins, M., Cooper, A., Cox, P.M., Depledge, J., Drummond, P., Ekins, P., Galaz, V., Grace, D., Graham, H., Grubb, M., Haines, A., Hamilton, I., Hunter, A., Jiang, X., Li, M., Kelman, I., Liang, L., Lott, M., Lowe, R., Luo, Y., Mace, G., Maslin, M., Nilsson, M., Oreszczyn, T., Pye, S., Quinn, T., Svensdotter, M., Venevsky, S., Warner, K., Xu, B., Yang, J., Yin, Y., Yu, C., Zhang, Q., Gong, P., Montgomery, H., Costello, A., 2015. Health and climate change: policy responses to protect public health. The Lancet 386(10006), 1861-1914.

Weber, T., Bowyer, P., Rechid, D., Pfeifer, S., Raffaele, F., Remedio, A.R., Teichmann, C., Jacob, D., 2020. Analysis of compound climate extremes and exposed population in Africa under two different emission scenarios. Earth's Future 8(9), e2019EF001473.

Wehrli, K., Guillod, B.P., Hauser, M., Leclair, M., Seneviratne, Sonia I., 2019. Identifying key driving processes of major recent heat waves. J. Geophys. Res-Atmos. 124(22), 11746-11765.

Weiland, R.S., van der Wiel, K., Selten, F., Coumou, D., 2021. Intransitive atmosphere dynamics leading to persistent hot–dry or cold–wet European summers. J. Climate 34(15), 6303-6317.

Weiss, J.L., Castro, C.L., Overpeck, J.T., 2009. Distinguishing pronounced droughts in the southwestern United States: seasonality and effects of warmer temperatures. J. Climate 22(22), 5918-5932.

Whan, K., Zscheischler, J., Jordan, A.I., Ziegel, J.F., 2021. Novel multivariate quantile mapping methods for ensemble post-processing of medium-range forecasts. Weather Clim. Extrem. 32, 100310.

Whan, K., Zscheischler, J., Orth, R., Shongwe, M., Rahimi, M., Asare, E.O., Seneviratne, S.I., 2015. Impact of soil moisture on extreme maximum temperatures in Europe. Weather Clim. Extrem. 9, 57-67.

Woodhouse, C.A., Pederson, G.T., Morino, K., McAfee, S.A., McCabe, G.J., 2016. Increasing influence of air temperature on upper Colorado River streamflow. Geophys. Res. Lett. 43(5), 2174-2181.

Woollings, T., Barriopedro, D., Methven, J., Son, S.-W., Martius, O., Harvey, B., Sillmann, J., Lupo, A.R., Seneviratne, S., 2018. Blocking and its response to climate change. Curr. Clim. Change Rep. 4(3), 287-300.

Wouters, H., Keune, J., Petrova, I.Y., Heerwaarden, C.C.v., Teuling, A.J., Pal, J.S., Arellano, J.V.-G.d., Miralles, D.G., 2022. Soil drought can mitigate deadly heat stress thanks to a reduction of air humidity. Sci. Adv. 8(1), eabe6653.

Wright, C.K., De Beurs, K.M., Henebry, G.M., 2014. Land surface anomalies preceding the 2010 Russian heat wave and a link to the North Atlantic oscillation. Environ. Res. Lett. 9(12), 124015.

Wu, D., Zhao, X., Liang, S., Zhou, T., Huang, K., Tang, B., Zhao, W., 2015. Time-lag effects of global vegetation responses to climate change. Global. Change. Biol. 21(9), 3520-3531.

Wu, H., Su, X., Singh, V.P., 2021a. Blended dry and hot events index for monitoring dry-hot events over global land areas. Geophys. Res. Lett. 48(24), e2021GL096181.

Wu, L.-Y., 2014. Changes in the covariability of surface air temperature and precipitation over east Asia associated with climate shift in the late 1970s. Atmos. Oceanic Sci Lett. 7(2), 92-97.

Wu, R., Chen, J., Wen, Z., 2013. Precipitation-surface temperature relationship in the IPCC CMIP5 models. Earth Space Sci. 30(3), 766-778.

Wu, X., Hao, Z., Hao, F., Singh, V.P., Zhang, X., 2019a. Dry-hot magnitude index: a joint indicator for compound event analysis. Environ. Res. Lett. 14(6), 064017.

Wu, X., Hao, Z., Hao, F., Zhang, X., 2019b. Variations of compound precipitation and temperature extremes in China during 1961–2014. Sci. Total. Environ. 663, 731-737.

Wu, X., Hao, Z., Hao, F., Zhang, X., Singh, V.P., Sun, C., 2021b. Influence of large-scale circulation patterns on compound dry and hot events in China. J. Geophys. Res-Atmos. 126(4), e2020JD033918.

Wu, X., Hao, Z., Tang, Q., Singh, V.P., Zhang, X., Hao, F., 2021c. Projected increase in compound dry and hot events over global land areas. Int. J. Climatol. 41(1), 393-403.

Wu, X., Hao, Z., Tang, Q., Zhang, X., Feng, S., Hao, F., 2021d. Population exposure to compound dry and hot events in China under 1.5 and 2 °C global warming. Int. J. Climatol. 41(12), 5766-5775.

Wu, X., Hao, Z., Zhang, X., Li, C., Hao, F., 2020. Evaluation of severity changes of compound dry and hot events in China based on a multivariate multi-index approach. J. Hydrol. 583, 124580.

Wu, X., Hao, Z., Zhang, Y., Zhang, X., Hao, F., 2022. Anthropogenic influence on compound dry and hot events in China based on Coupled Model Intercomparison Project Phase 6 models. Int. J. Climatol. 42(8), 4379-4390.

Wu, Y., Miao, C., Sun, Y., AghaKouchak, A., Shen, C., Fan, X., 2021e. Global observations and CMIP6 simulations of compound extremes of monthly temperature and precipitation. GeoHealth 5(5), e2021GH000390.

Xia, Y., Hao, Z., Shi, C., Li, Y., Meng, J., Xu, T., Wu, X., Zhang, B., 2019. Regional and global land data assimilation systems: Innovations, challenges, and prospects. J. Meteorol. 33(2), 159-189.

Xu, F., Luo, M., 2019. Changes of concurrent drought and heat extremes in the arid and semi-arid regions of China during 1961–2014. Atmos Sci. Lett. 20(12), e947.

Xu, P., Wang, L., Huang, P., Chen, W., 2021. Disentangling dynamical and thermodynamical contributions to the record-breaking heatwave over Central Europe in June 2019. Atmos. Res. 252, 105446.

Yao, H., Zhao, L., Shen, X., Xiao, Z., Li, Q., 2022. Relationship between summer compound hot and dry extremes in China and the snow cover pattern in the preceding winter. Front. Earth Sci. 10, 834284.

Yin, H., Donat Markus, G., Alexander Lisa, V., Sun, Y., 2014. Multi-dataset comparison of gridded observed temperature and precipitation extremes over China. Int. J. Climatol. 35(10), 2809-2827.

Yiou, P., Jézéquel, A., 2020. Simulation of extreme heat waves with empirical importance sampling. Geosci. Model Dev. 13(2), 763-781.

Yu, R., Zhai, P., 2020a. Changes in compound drought and hot extreme events in summer over populated eastern China. Weather Clim. Extrem. 30, 100295.

Yu, R., Zhai, P., 2020b. More frequent and widespread persistent compound drought and heat event observed in China. Sci. Rep. 10(1), 14576.

Yuan, X., Wang, L., Wood, E.F., 2018. Anthropogenic intensification of southern African flash droughts as exemplified by the 2015/16 season. Bull. Amer. Meteor. Soc 99(1), S86-S90.

Zampieri, M., Ceglar, A., Dentener, F., Toreti, A., 2017. Wheat yield loss attributable to heat waves, drought and water excess at the global, national and subnational scales. Environ. Res. Lett. 12, 064008.

Zampieri, M., D'Andrea, F., Vautard, R., Ciais, P., de Noblet-Ducoudré, N., Yiou, P., 2009. Hot european summers and the role of soil moisture in the propagation of Mediterranean drought. J. Climate 22(18), 4747-4758.

Zappa, M., Kan, C., 2007. Extreme heat and runoff extremes in the Swiss Alps. Nat. Hazards Earth Syst. Sci. 7(3), 375-389.

Zhai, P., Zhou, B., Chen, Y., 2018. A review of climate change attribution studies. J. Meteorol. 32(5), 671-692.

Zhan, W., He, X., Sheffield, J., Wood, E.F., 2020. Projected seasonal changes in large-scale global precipitation and temperature extremes based on the CMIP5 ensemble. J. Climate 33(13), 5651-5671.

Zhang, H., Wu, C., Yeh, P.J.-F., Hu, B.X., 2020a. Global pattern of short-term concurrent hot and dry extremes and its relationship to large-scale climate indices. Int. J. Climatol. 40: (14), 5906–5924.

Zhang, P., Jeong, J.-H., Yoon, J.-H., Kim, H., Wang, S.-Y.S., Linderholm, H.W., Fang, K., Wu, X., Chen, D., 2020b. Abrupt shift to hotter and drier climate over inner East Asia beyond the tipping point. Science 370(6520), 1095-1099.

Zhang, W., Luo, M., Gao, S., Chen, W., Hari, V., Khouakhi, A., 2021a. Compound hydrometeorological extremes: drivers, mechanisms and methods. Front. Earth Sci. 9, 673495.

Zhang, X., Hao, Z., Singh, V.P., Zhang, Y., Feng, S., Xu, Y., Hao, F., 2022a. Drought propagation under global warming: Characteristics, approaches, processes, and controlling factors. Sci. Total. Environ. 838, 156021.

Zhang, X., Zhang, B., 2019. The responses of natural vegetation dynamics to drought during the growing season across China. J. Hydrol. 574, 706-714.

Zhang, Y., Hao, Z., Feng, S., Zhang, X., Hao, F., 2022b. Changes and driving factors of compound agricultural droughts and hot events in eastern China. Agr. Water Manage. 263, 107485.

Zhang, Y., Hao, Z., Feng, S., Zhang, X., Hao, F., 2022c. Comparisons of changes in compound dry and hot events in China based on different drought indicators. Int. J. Climatol. in press.

Zhang, Y., Hao, Z., Zhang, X., Hao, F., 2022d. Anthropogenically forced increases in compound dry and hot events at the global and continental scales. Environ. Res. Lett. 17(2), 024018.

Zhang, Y., Keenan, T.F., Zhou, S., 2021b. Exacerbated drought impacts on global ecosystems due to structural overshoot. Nat. Ecol. Evol. 5, 1490–1498.

Zhang, Y., You, Q., Mao, G., Chen, C., Ye, Z., 2019. Short-term concurrent drought and heatwave frequency with 1.5 and 2.0 °C global warming in humid subtropical basins: a case study in the Gan River Basin, China. Clim. Dynam. 52(7), 4621-4641.

Zhao, W., Khalil, M., 1993. The relationship between precipitation and temperature over the contiguous United States. J. Climate 6, 1232-1240.

Zhou, P., Liu, Z., 2018. Likelihood of concurrent climate extremes and variations over China. Environ. Res. Lett. 13(9), 094023.

Zhou, S., Williams, A.P., Berg, A.M., Cook, B.I., Zhang, Y., Hagemann, S., Lorenz, R., Seneviratne, S.I., Gentine, P., 2019. Land–atmosphere feedbacks exacerbate concurrent soil drought and atmospheric aridity. Proc. Natl. Acad. Sci. 116(38), 18848-18853.

Zhou, S., Yuan, X., 2022. Upwind droughts enhance half of the heatwaves over north China. Geophys. Res. Lett. 49(2), e2021GL096639.

Zhu, P., Abramoff, R., Makowski, D., Ciais, P., 2021. Uncovering the past and future climate drivers of wheat yield shocks in Europe with machine learning. Earth's Future 9(5), e2020EF001815.

Zhu, X., Troy, T.J., 2018. Agriculturally relevant climate extremes and their trends in the world's major growing regions. Earth's Future 6(4), 656-672.

Zhu, Z., Piao, S., Xu, Y., Bastos, A., Ciais, P., Peng, S., 2017. The effects of teleconnections on carbon fluxes of global terrestrial ecosystems. Geophys. Res. Lett. 44(7), 3209-3218.

Zscheischler, J., Fischer, E.M., 2020. The record-breaking compound hot and dry 2018 growing season in Germany. Weather Clim. Extrem. 29, 100270.

Zscheischler, J., Fischer, E.M., Lange, S., 2019. The effect of univariate bias adjustment on multivariate hazard estimates. Earth Syst. Dynam. 10(1), 31-43.

Zscheischler, J., Lehner, F., 2022. Attributing compound events to anthropogenic climate change. Bull. Amer. Meteor. Soc 103(3), E936-E953.

Zscheischler, J., Martius, O., Westra, S., Bevacqua, E., Raymond, C., Horton, R.M., van den Hurk, B., AghaKouchak, A., Jézéquel, A., Mahecha, M.D., Maraun, D., Ramos, A.M., Ridder, N.N., Thiery, W., Vignotto, E., 2020. A typology of compound weather and climate events. Nat. Rev. Earth Environ. 1, 333–347.

Zscheischler, J., Michalak, A.M., Schwalm, C., Mahecha, M.D., Huntzinger, D.N., Reichstein, M., Berthier, G., Ciais, P., Cook, R.B., El-Masri, B., Huang, M., Ito, A., Jain, A., King, A., Lei, H., Lu, C., Mao, J., Peng, S., Poulter, B., Ricciuto, D., Shi, X., Tao, B., Tian, H., Viovy, N., Wang, W., Wei, Y., Yang, J., Zeng, N., 2014. Impact of large-scale climate extremes on biospheric carbon fluxes: An intercomparison based on MsTMIP data. Global Biogeochem. Cy 28(6), 585-600.

Zscheischler, J., Naveau, P., Martius, O., Engelke, S., C. Raible, C., 2021. Evaluating the dependence structure of compound precipitation and wind speed extremes. Earth Syst. Dynam. 12(1), 1-16.

Zscheischler, J., Orth, R., Seneviratne, S.I., 2017. Bivariate return periods of temperature and precipitation explain a large fraction of European crop yields. Biogeosciences 14(13), 3309-3320.

Zscheischler, J., Seneviratne, S.I., 2017. Dependence of drivers affects risks associated with compound events. Sci. Adv. 3(6), e1700263.

Zscheischler, J., Westra, S., van den Hurk, B., Seneviratne, S.I., Ward, P.J., Pitman, A., AghaKouchak, A., Bresch, D.N., Leonard, M., Wahl, T., Zhang, X., 2018. Future climate risk from compound events. Nat. Clim. Change. 8(6), 469-477.

13 Table 1 Advances, challenges, and future dictions 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
Characterization	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

14 Figure

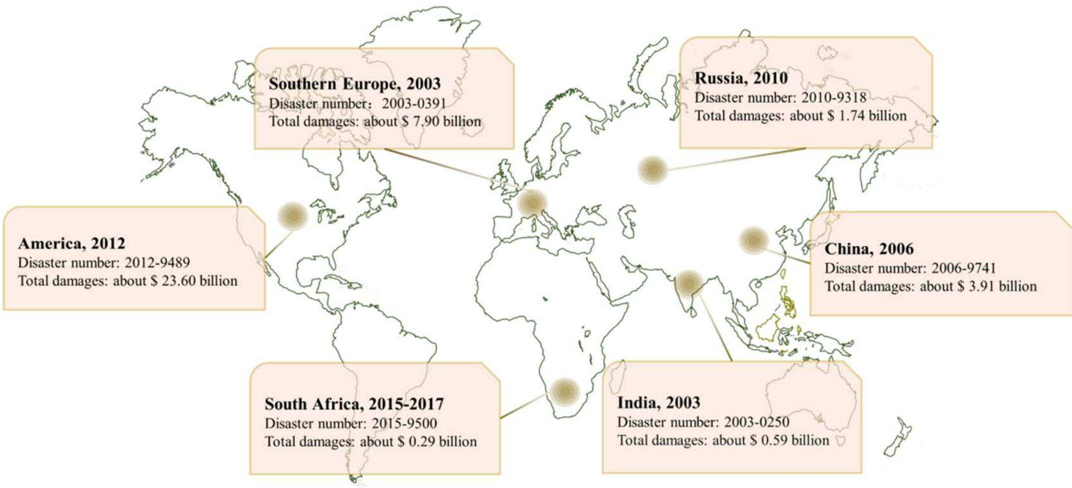

Figure 1 Illustrations of several concurrences of droughts and hot extremes in the past few decades across the globe. These events are identified from the Emergency Events Database (EM-DAT).

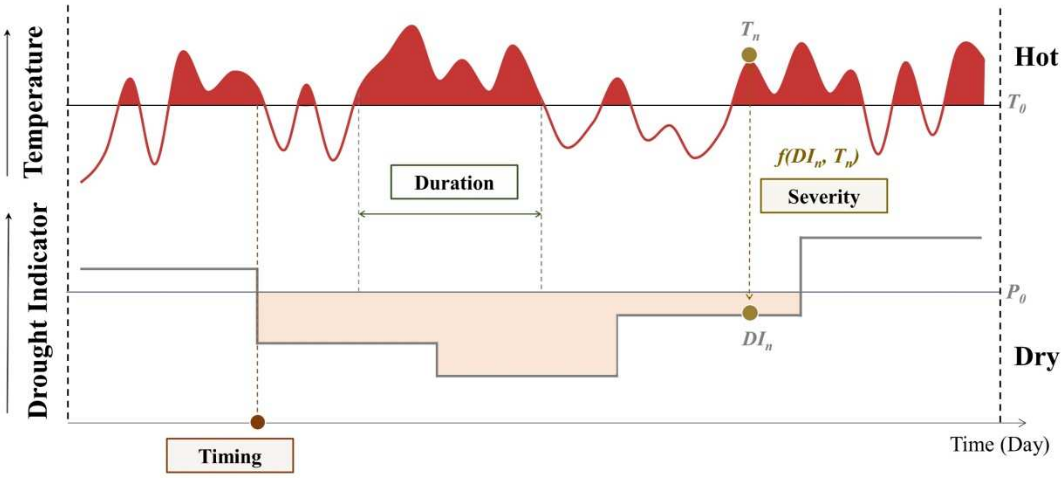

Fig. 2 Illustration of different properties of compound droughts and hot events (CDHEs) including duration, timing, and severity based on drought indicator (DI) and temperature. The severity is defined as the function of properties of drought indicator (DI) and temperature (T).

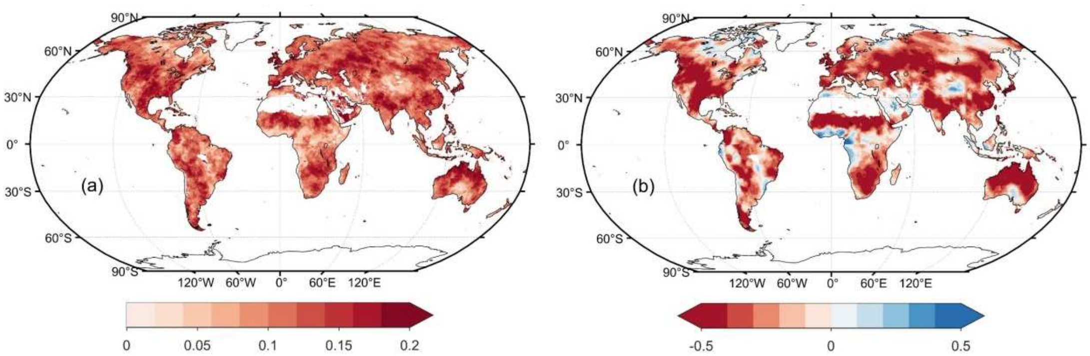

Fig. 3 Climatology frequency of CDHEs and precipitation-temperature dependence of the warm season (JJA for the Northern Hemisphere and DJF for the Southern Hemisphere) based on monthly precipitation and temperature data from Climatic Research Unit (CRU) for the period 1951-2018. The 30th percentile and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

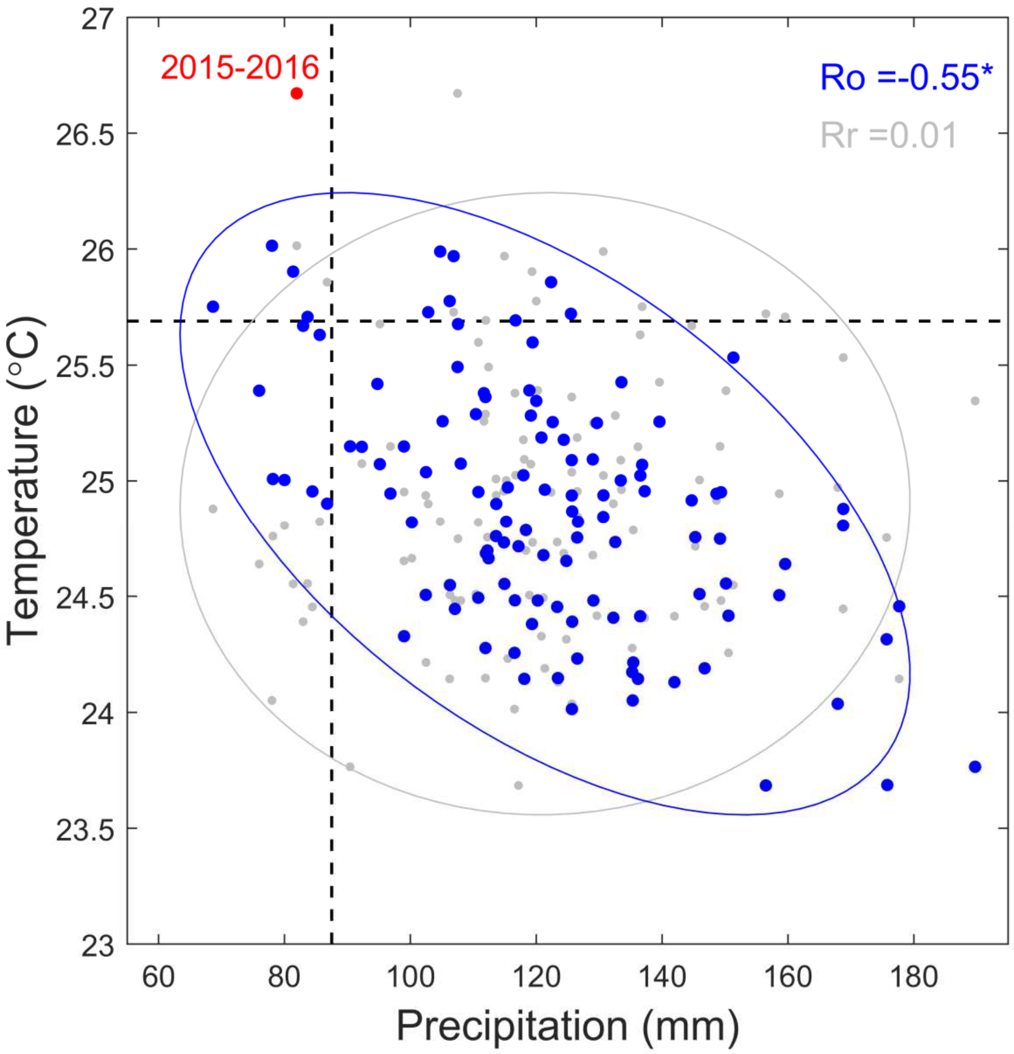

Fig. 4 Scatterplot of observed average precipitation and temperature for DJF from 1901 to 2018 in southern Africa based on monthly data from CRU (blue dots). The gray dots indicate values with randomly permutated temperature (Zscheischler and Seneviratne, 2017). Ro and Rr are correlation coefficients of the observed and random permutated 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 (red dots).

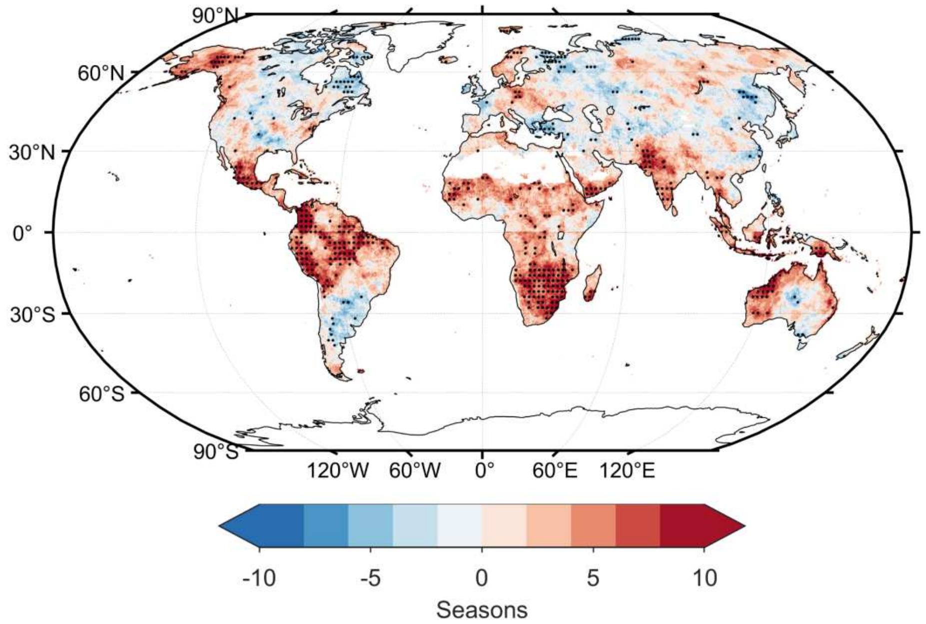

Fig. 5. Impact of ENSO on CDHEs during warm seasons (JJA for the Northern Hemisphere and DJF for the Southern Hemisphere) based on composite analysis. The monthly precipitation and temperature data are obtained from CRU for the period 1951-2018. The 30th percentile and 70th percentile of precipitation 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.

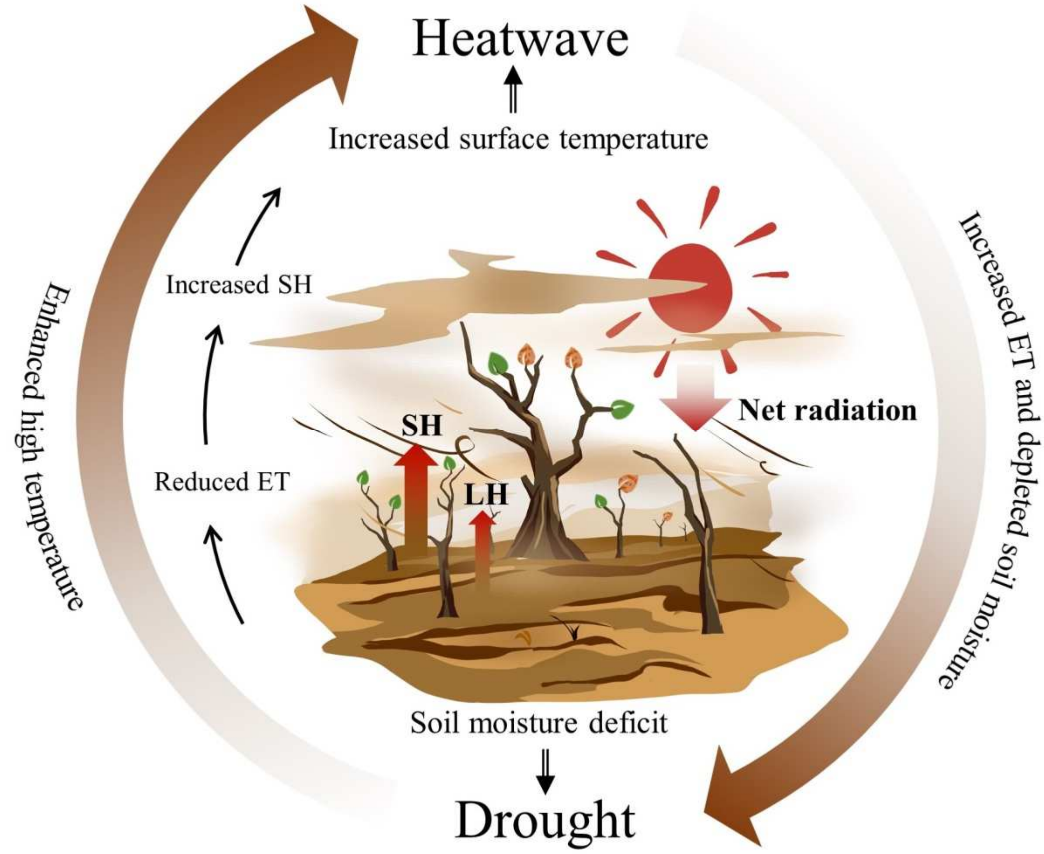

Fig. 6 Illustration of the occurrence of concurrent droughts and heatwaves from the soil moisture-temperature feedbacks. Revised from Perkins (2015) and Alexander (2011). ET, SH, and LH are the abbreviation of evapotranspiration, sensible heat, and latent heat, respectively.

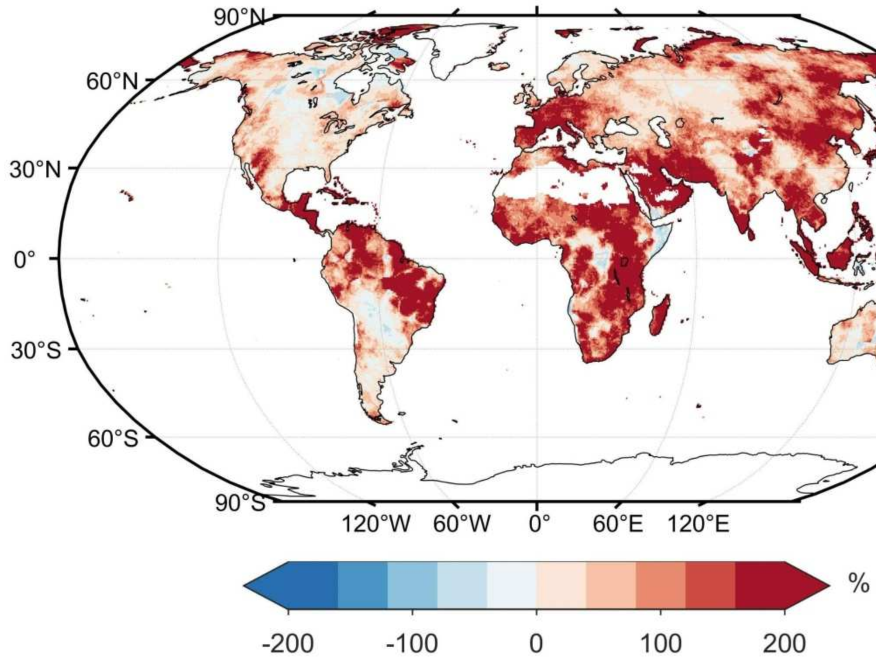

Fig. 7 Changes in the annual frequency of CDHEs between 1951–1984 and 1985–2018 based on monthly precipitation and temperature data from CRU. The 30th percentile and 70th percentile of precipitation and temperature, respectively, are used as thresholds to define CDHEs. Revised from Hao et al. (2013).

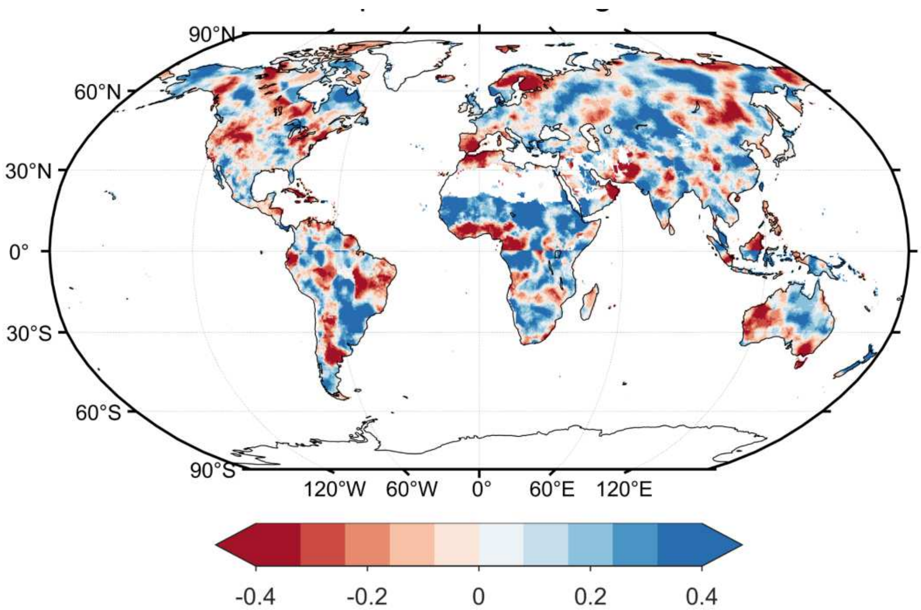

Fig. 8 Changes in the precipitation-temperature correlations of the warm season (JJA for the Northern Hemisphere and DJF for the Southern Hemisphere) for two equal periods 1951-1984 and 1985-2018 based on the CRU data. Revised from Hao et al. (2019c).

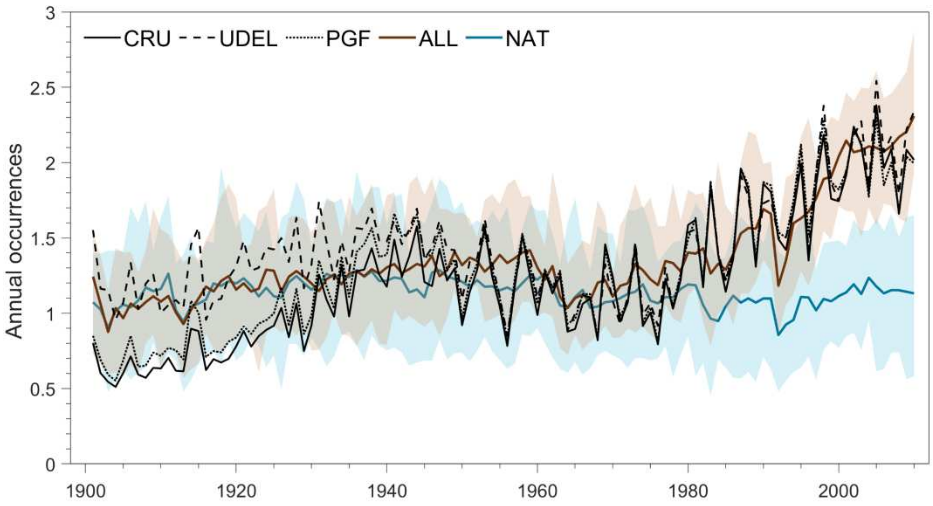

Fig. 9 Temporal change in annual occurrences of CDHEs (average number of events per years across the globe) based on observations and CMIP6 all forcings (ALL) and natural forcings (NAT) simulations for the period from 1901 to 2010. The observations of monthly precipitation and temperature data include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

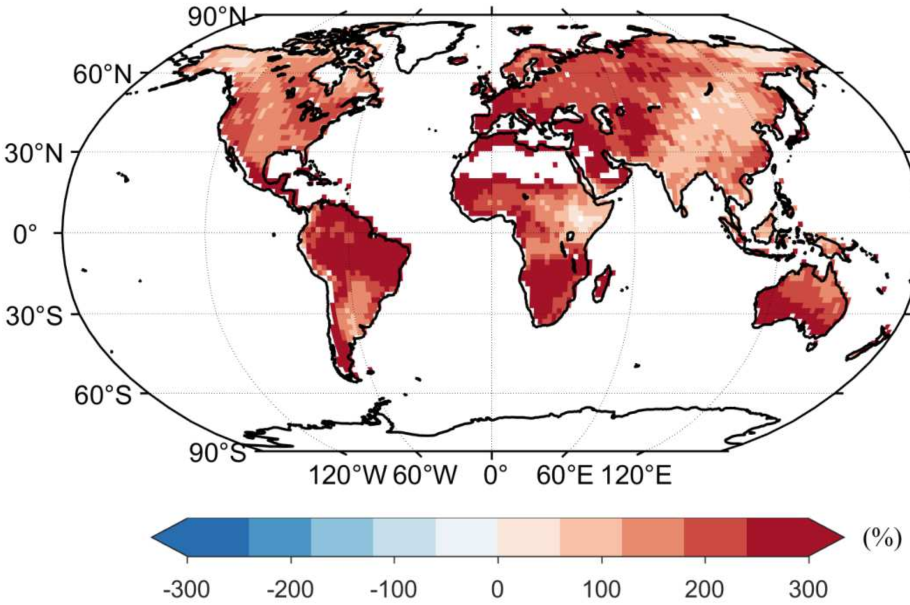

Fig. 10 Relative changes in the annual occurrences of CDHEs between 1986-2005 and 2081-2100 at the global scale based on CMIP6 simulations under SSP5-8.5. Revised from Meng et al. (2022b).

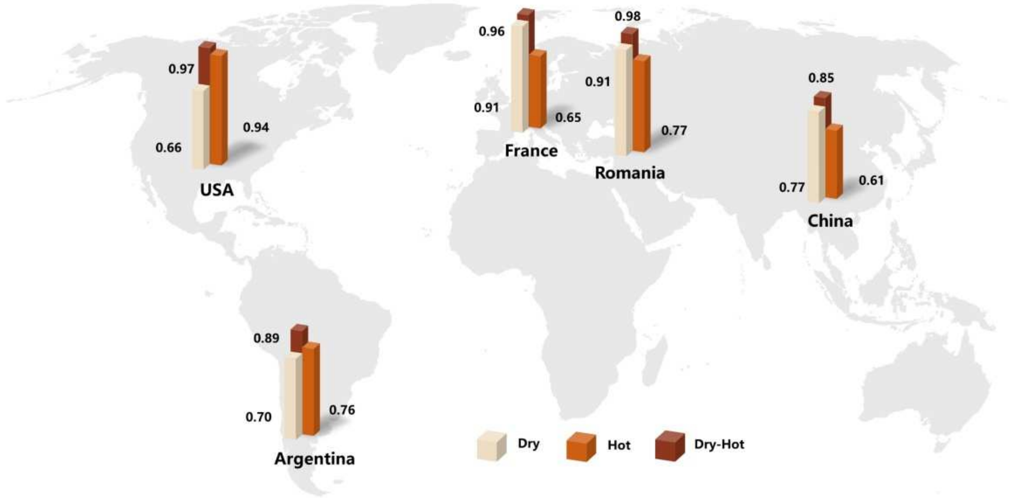

Fig. 11 The demonstration of the impact of CDHEs on crop yield for the top five maize-producing countries based on Standardized Precipitation Index (SPI), Standardized Temperature Index (STI), and Standardized Crop yield Index (SCI). The conditional probability of crop yield loss (SCI<0) given different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