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# Broadening the scope of anthropogenic influence in extreme event attribution

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Abstract

As extreme event attribution (EEA) matures, explaining the impacts of extreme events has risen to be a key focus for attribution scientists. Studies of this type usually assess the contribution of anthropogenic climate change to observed impacts. Other scientific communities have developed tools to assess how human activities influence impacts of extreme weather events on ecosystems and societies. For example, the disaster risk reduction (DRR) community analyses how the structure of human societies affects exposure, vulnerability, and ultimately the impacts of extreme weather events, with less attention to the role of anthropogenic climate change. In this perspective, we argue that adapting current practice in EEA to also consider other causal factors in attribution of extreme weather impacts would provide richer and more comprehensive insight into the causes of disasters. To this end, we propose a framework for EEA that would generate a more complete picture of human influences on impacts and bridge the gap between the EEA and DRR communities. We provide illustrations for five case studies: the 2021-2022 Kenyan drought; the 2013-2015 marine heatwave in the northeast Pacific; the 2017 forest fires in Portugal; Acqua Alta (flooding) events in Venice and evaluation of the efficiency of the Experimental Electromechanical Module (MoSE), an ensemble of mobile barriers that can be activated to mitigate the influx of seawater in the city; and California droughts and the Forecast Informed Reservoir Operations (FIRO) system as an adaptation strategy,

## 1) Introduction

Scientific frameworks to attribute the occurrence of an extreme weather event to anthropogenic climate change have been discussed at least since 2003, when Allen (2003) introduced the idea of comparing the probability of occurrence of an event in the *factual world*, i.e., the world as we know it, to its probability in a *counterfactual world*, i.e., a world that could have been, in the absence of climate change. This idea is also commonly used in epidemiological research (Maldonado and Greenland, 2002), with the goal to attribute changes in the odds of a certain event, e.g. developing lung cancer, to underlying factors such as exposure to asbestos. Stott et al. (2004) provided the first application of this framework through analysing the 2003 European heatwave and showing that anthropogenic climate change had at least doubled the likelihood of the heatwave. Since then, the science of extreme event attribution (EEA) has developed in several directions, through different approaches to the contextualisation of observed events in a changing climate (Jézéquel et al., 2018; Otto, 2017; Shepherd, 2016; Trenberth et al., 2015) and different methodologies (e.g. Faranda et al., 2022; Meredith et al., 2015; Pall et al., 2011; Robin and Ribes, 2020).

While the first studies focused mainly on extreme heat, attribution is now covering growing numbers of weather extremes such as heavy precipitation (e.g. Tradowsky et al., 2023), droughts (e.g. Uhe et al., 2018), cyclones (e.g. Risser and Wehner, 2017), fire or wildfire danger (e.g. Abram, 2021; van Oldenborgh et al., 2021), and marine heatwaves (e.g. Li et al., 2023), with the development of methodologies to deal with compound events (Qian et al., 2023; Zscheischler and Lehner, 2022).

However, human influence on climate-driven catastrophes goes beyond the potential influence of anthropogenic climate change on extreme weather events. For example, water consumption can lead to anthropogenic droughts (AghaKouchak et al., 2021, 2015; Van Loon et al., 2016) and it has been shown that water management practices aggravate both streamflow droughts (Van Loon et al., 2022) and groundwater depletion (e.g. Ashraf et al., 2021; Wendt et al., 2020). Similarly, forest management and ecological dynamics (e.g. forest structure, phenology, pathogens) play key roles in ecological disturbance events (Bastos et al., 2023), and direct effects of elevated $CO_2$ and nutrient deposition on plant growth impose changes beyond climate change itself (Walker et al., 2021). Zhang et al. (2018) showed the role played by urbanization to exacerbate both the rain and the flooding caused by Hurricane Harvey.

Since one of the motivations for extreme event attribution is to understand the impacts of climate change on human societies, rather than its effects on extreme weather events alone, recent literature has sought to extend attribution methods to the impacts of those weather events. Such studies have typically relied either on tailored statistical analyses such as transfer functions or Bayesian regression models commonly used in epidemiological studies (Frame et al., 2020b, 2020a; Litzow et al., 2021; Mitchell et al., 2016; Vicedo-Cabrera et al., 2023, 2021), or on dynamical impact models, deriving impacts in both the factual and counterfactual worlds obtained from climate models (Schaller et al., 2016; Sebastian et al., 2019; Sippel et al., 2017; Smiley et al., 2022; Wehner and Sampson, 2021). The type of impact studied and disciplines required to evaluate them varies. Key developments have been done through collaborations with epidemiologists (Mitchell et al., 2016; Vicedo-Cabrera et al., 2023), hydrologists (Schaller et al., 2016; Sebastian et al., 2019; Wehner and Sampson, 2021) and economists (Frame et al., 2020a, 2020b; Newman and Noy, 2023). These studies use the climate risk framework, namely describing impacts that are the result of the combination of hazards, exposure and vulnerability of populations or assets, and sometimes societal response to hazards that mediate or amplify their impact (Simpson et al., 2021).

The use of impact models is usually specific to the context within the area where the event occurred, thus requiring local model verification. Models that aim to represent the relationship between drivers and impacts are also affected by epistemic uncertainty, caused by the lack of data and the complex interactions between society and impactful events. It is often unclear to what extent past observations of drivers and impacts can be used, how they may change over time due to changes in vulnerability or exposure, and whether they can accurately describe the most extreme events (Rufat et al., 2015). For example, during long-lasting extreme events such as droughts and heatwaves, impacted people respond during the event, causing dynamic vulnerability and therefore changing the impacts even during the event (Ruiter and Van Loon, 2022). The same can be said for ecosystems, where for example, responses to hot-dry conditions in spring might contribute to summer water depletion (Bastos et al., 2020) and ecosystem vulnerability to summer drought (Buermann et al., 2018). After a particularly impactful event, response systems may improve such that a very similar event a few years later has a much smaller impact (Fouillet et al., 2008; Kreibich et al., 2017a, 2022).

The current perspective on EEA, including attribution of impacts, highlights human influence on these impacts only through climate change, by quantifying how the hazard leading to the disaster was impacted by greenhouse gas emissions (Mengel et al., 2021). Establishing the link between these

emissions and impactful weather events is key to highlighting the emitters' responsibilities in current climate-driven impacts. However, a too climate-centric perspective poses the risk of limiting the attribution of the impacts of extreme weather events to greenhouse gas and aerosol emissions, and thereby making the role of other anthropogenic drivers of disasters, in particular dynamic vulnerability and maladaptation, invisible (Wisner, 2016) and blaming the climate for disasters (Raju et al., 2022). Most of the attribution studies cited above attribute the role of *human-driven* changes in the vulnerability and exposure leading to impacts, but are limited to the attribution of impacts to climate drivers. Sebastian et al. (2019) disentangled the impacts of urbanization and climate change on catchment response during Hurricane Harvey. They built three counterfactuals: pre-development conditions, urbanization without climate change, and climate change without urbanization. They found that urban development alone increased peak discharges by 54% (±28%) and climate change alone increased them by 20% (±3%) with a combined effect of 84% (±35%). This shows the potential of such studies to highlight the compound effect of two anthropogenic changes.

Another scientific community working on impactful extreme weather events is the Disaster Risk Reduction (DRR) community. DRR spans a wide range of hazards, including earthquakes, volcanic eruptions, landslides, floods, tsunamis, and sometimes also man-made or technological hazards such as chemical spills, dam failures and nuclear meltdowns (Brinkmann, 2020). Climate change adaptation is the branch of DRR that focuses on climate-related hazards. We will use the term DRR in the remainder of this text. For example, Meza et al (2020) assess the different components of risk (hazard, exposure and vulnerability) for agricultural drought at the global scale. Ward et al. (2013) assess global flood risk using a model cascade that includes hydrological and hydraulic modelling, extreme value statistics, inundation modelling, flood impact modelling, and estimating annual expected impacts. The DRR community is more focused on the quantification of risk, so the chance that something might happen, than on looking at a specific event and attributing the drivers of the event (see e.g. Blauhut (2020) for a drought risk review).

While the integration of DRR issues in EEA is a challenge, the same can be said of the integration of climate change as an additional layer of human influence on disasters within the DRR community. For example, Hsu et al. (2021) show inequalities in exposure to urban heat island intensity between populations of different ethnicities and different income, but their study does not take into account the evolution of urban heat island intensity in a changing climate. Similarly, Sanders et al. (2023) highlight that flooding risks are disproportionately higher for non-Hispanic Black and disadvantaged

populations in Los Angeles, but the evolution of these inequalities in the context of climate change is not discussed. Van Loon et al. (2022) also analyse direct human influences on streamflow drought without taking into consideration trends caused by climate change.

Taking into account the non-stationarity of hazards (for example, the changes—especially increases—in disaster risk due to flooding, drought, or fire getting more frequent and/or intense because of anthropogenic climate change) in DRR studies is important, because with changes in extreme event characteristics, neighbourhoods once deemed safe become newly exposed to hazards, causing the monetary value of their properties to plummet (Köhler et al., 2023). This traps the most exposed residents - who cannot afford to move out - making them vulnerable, and the neighbourhood retains only the most vulnerable groups, hollowing out any adaptation action (Rufat et al., 2020).

EEA adds an event perspective to the risk discussion and provides a new basis to attribute responsibilities for disaster impacts. It can be used to underline the causal link between emissions and losses in a context of climate justice (Otto et al., 2022). However, highlighting the contribution of humans to disasters through anthropogenic climate change may paradoxically hinder efforts from the DRR community to "take the naturalness out of the natural disasters" (O'Keefe et al., 1976), by (re)focusing attention on the hazard instead of vulnerability. Lahsen and Ribot (2022) have shown how "climate-centric framings of disasters" can be used as a way for local politicians to shirk responsibilities in the aftermath of a disaster (see also Grant et al (2015) on "climatization" of cyclone impacts in Bangladesh, Savelli et al (2021) on the 2015-2017 drought in Cape Town, and Lahsen et al (2020) for two Brazilian case studies). Narratives overemphasizing the role of climate change in crises such as the Syrian war or African migrations have also been challenged (Fröhlich, 2016; Ribot et al., 2020; Selby et al., 2017), and pose problems in terms of what this climatization of conflicts might mean for international policies and agendas (Lahsen and Ribot, 2022).

To our knowledge, the only EEA study so far to address human influence on both the hazard, and a part of vulnerability and exposure is Sebastian et al. (2019) by quantifying the roles of both climate change and urbanization on Hurricane Harvey's peak discharge. There are however many examples of detection and attribution of trends in biophysical variables to different types of anthropogenic factors. Vicente-Serrano et al. (2019) attribute streamflow trends in countries bordering the Northeast Atlantic to climate, irrigation and land-cover changes. Litzow et al. (2014) discuss biological variability in the North Pacific in the context of both climate change and commercial fishing. Tait et al. (2021) found that poor water clarity, partly driven by extensive land-use change,

amplified impacts from the 2017/18 marine heatwave off southern New Zealand on habitat-forming kelp forests.

To our knowledge, Smiley et al (2022) is the only EEA study focusing on social inequalities due to climate change in the context of an extreme event impact. They show that the increased flood depths attributed to climate change arising from Hurricane Harvey were particularly felt in Latina low-income neighbourhoods. While not an attribution study, Rusca et al. (2023) highlight how unprecedented droughts that are projected to happen in future scenarios could exacerbate urban inequalities in Southern Africa. These studies indicate how information on climate hazards can be synthesised with vulnerability information to assess different contributions to risk.

Here we propose a multidimensional framework for EEA, built on the framework proposed by Bastos et al. (2023) to study compound eco-climatic events. The goal is to bridge the EEA and DRR communities and to provide insight into the contributions made by climate change and other factors to disaster losses. This new framework could help to enhance knowledge about the causes of climate-related impacts by including both the effects of anthropogenic climate change and other human influences on risk by building *pertinent counterfactual and factual* worlds, based on an inclusive co-construction process between scientists, decision makers, and the most vulnerable communities. It also aligns with a push within the EEA community to propose frameworks grounded in causally understood processes — so-called storylines — able to include different approaches and methodologies of EEA (e.g. Lloyd and Shepherd, 2023, 2020).

We first explain the general framework, which can be used as a canvas describing the general picture of the event and its causes. Furthermore, we provide illustrations for five case studies: the 2021-2022 Kenyan drought; the 2013-2015 marine heatwave in the northeast Pacific; the 2017 forest fires in Portugal; Acqua Alta (flooding) events in Venice and evaluation of adaptation strategies; and California droughts and the Forecast Informed Reservoir Operations (FIRO) system as an adaptation strategy. We discuss how our approach could be applied qualitatively and quantitatively, based on the current state of the art and highlight the limitations and opportunities. We conclude with a discussion of the advantages and limitations of our framework.

## 2) General framework

### a) Differences of vocabulary

While the framework we present in this paper relies on the commonly used climate risk perspective (Simpson et al., 2021) where impacts result from the combination of hazard, exposure and vulnerability, these words can cover a wide range of meanings depending on the disciplinary context in which they are used. For example, while a flood would be considered a hazard in the DRR community, the climate science community would consider it an impact, in which case the hazard would be, e.g., a storm or heavy precipitation. Similarly, for droughts: from the climate perspective, low soil moisture or groundwater levels could be seen as impacts, but from the DRR perspective these are regarded as hazards and the impact arises only when the social system is affected.

As a consequence, the meanings of vulnerability and exposure also vary from one community to another. In DRR, vulnerability is broadly defined as the potential to disproportionately suffer loss, harm or longer recovery, with a focus on finding the “root causes” and dynamic pressures that produce vulnerability (Wisner, 2016). Vulnerability can be divided into physical or biophysical vulnerability of people and places to hazards and extreme events, structural vulnerability of buildings and lifelines, as well as social vulnerability, describing differential susceptibility based on social, economic and political factors (Burton et al., 2018). Physical vulnerability is sometimes conflated with hazard exposure in a DRR context (see for examples De Sherbinin et al., 2019), but for the climate community, vulnerability often only encompasses exposure or damages (e.g. Formetta and Feyen, 2019) as a result of a focus on impacts rather than the processes and root causes of DRR.

These differences of meaning matter as they tend to highlight some parts of the chain of causation more than others and can hence conceal some parts of the processes at work. They also influence the framing around disaster causes and potential solutions, which has consequences when the science is communicated to decision makers. A focus on the social determinants of vulnerability can help explain why people with similar levels of exposure may experience very different levels of adverse impact (Kuhlicke et al., 2023). For example, the African-American communities have borne a disproportionate burden following Hurricane Katrina (Colten, 2006), studies across continents highlight that floods disproportionately affect lower-socioeconomic status households (Rufat et al., 2015), whereas the recent drought and flood events in the Horn of Africa combined with ethnic conflict in Ethiopia and Kenya, leading to displacement, further violence and mutually reinforcing interactions (Matanó et al., 2022). Social vulnerability arises as the result of a progression that proceeds from root causes through dynamic pressures to unsafe conditions. Root causes are societal scale and interrelated political, economic, and

demographic structures that establish and sustain power relationships, and govern the allocation of resources (Wisner, 2016). Whilst the importance of social and behavioural determinants of vulnerability and resilience has been addressed by a wide range of approaches, their multidimensionality makes it difficult to represent them with a universal set of metrics across scales and hazards (Rufat et al., 2019).

As already discussed in the introduction, anthropogenic influence also covers different realities in different scientific communities. On the climate side, this influence would generally be regarded to consist of greenhouse gases and aerosol emissions, while for example some studies on drought focus on anthropogenic influence in the form of water management practices.

It is neither realistic nor respectful to force very precise definitions of these words on different communities, beyond the generic definitions from the IPCC. It is however crucial to clarify the meaning of the words used in specific studies, in order to move forward on a more systemic approach to attribution of the impacts of disasters to anthropogenic forcing, so that scholars from different disciplines can understand each other and integrate their respective understanding of the role of human activities.

b) The framework

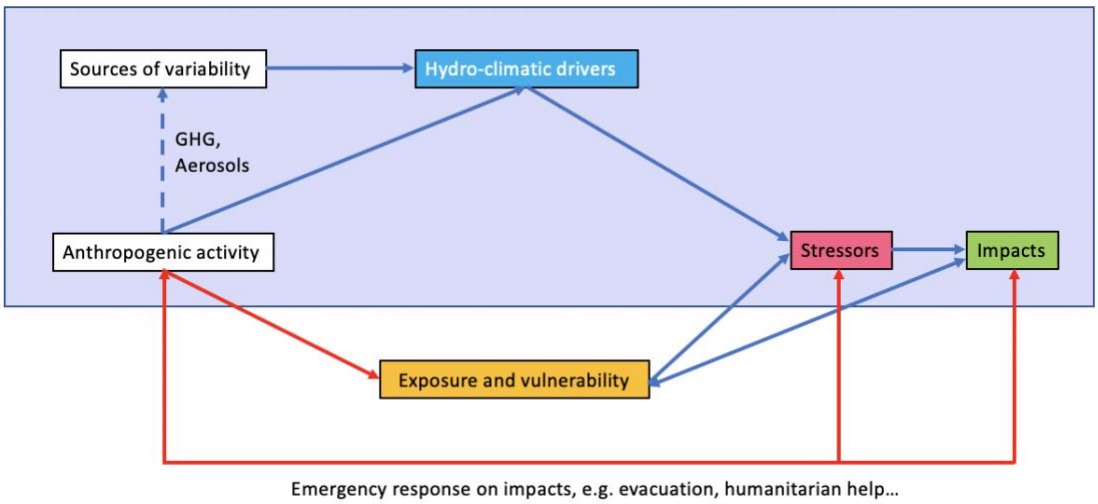



*Figure 1: Conceptual framework for a broader attribution of disasters to human influence, adapted from Bastos et al (2023)'s framework of ecoclimatic events (figure 2 of their work). The blue frame corresponds to a traditional EEA framework, The red arrows are generally not considered in EEA studies.*

Bastos et al. (2023) introduced a new framework to study eco-climatic events as a bridge between two approaches to analyse the impacts of climate extremes and disturbances on ecosystems: climate risk and disturbance ecology. This framework presents a causal chain between anthropogenic activities and ecological impacts. The key aspect that makes it relevant for our purpose is that it includes compounding characteristics that reflect the dynamic and complex relationships between climate, societies and impacts, hence highlighting the effect of anthropogenic activities on different steps of the causality chains towards impacts. It is an opportunity to move towards a more holistic perspective of the multi-causal charts that have been proposed for extreme attribution, such as Lloyd and Shepherd (2023, 2020) and for risk assessment (e.g. Hagenlocher et al., 2023). Bastos et al (2023)'s conceptual framework can be straightforwardly broadened to more types of impacts of climate extremes with a few changes, explained below. Figure 1 sums up our proposed conceptual framework for enhanced EEA. Concrete examples of how this framework could be applied to different types of events are given in sections 3 and 4.

*Hydro-climatic drivers* correspond to the extreme events that are called hazards in the climate science community. They would typically be climate or meteorological variables that would describe an extreme weather situation, either univariate or multivariate. These include for example extreme low and high temperatures, extreme precipitation or a lack of precipitation, high wind speed, and extreme values of relative humidity. From fields of basic meteorological variables, one can also explore diverse spatial and temporal scales, as well as compound weather events deriving from the interaction of anomalous states of these basic variables (Zscheischler, 2020; Zscheischler et al., 2018).

Hydro-climatic drivers can be affected by *anthropogenic activity* through the forced response of climate change, but also by *internal climate variability*. Internal variability may result in particular from well-known modes of variability that affect regional climate from seasonal to decadal scales, e.g. the El Nino Southern Oscillation (ENSO) (Goddard and Gershunov, 2020), the Indian Oscillation Dipole (IOD), or the Atlantic Meridional Oscillation (AMO) (Zhang, 2019). We note that internal climate variability may interact with anthropogenic climate change and thus modulate the severity of hazards, for example attenuate or reinforce (Karamperidou et al., 2020; Kimutai et al., 2022).

*Stressors* are defined, following Bastos et al. (2023), as "physical, chemical or biological phenomena that can impose changes" in ecosystems and social systems (such as people or infrastructures). While hydro-climatic drivers only describe weather and climate, stressors are one step closer to impacts,

including e.g. hydrological, chemical or biological processes. In the DRR literature, these are called hazards. They include for example anomalously high or low streamflow, soil moisture, groundwater levels, heat stress, air pollution, fire intensity, or fire extent. They can also be multivariate and affect different spatial and temporal scales.

Following a conventional disaster risk perspective, *exposure and vulnerability* include all the other social, economic and environmental factors that interact with stressors to lead to impacts. Similar to Bastos et al.'s definition, they can modulate both stressors and impacts. They include all the non-weather-related factors that influence climate-related risks, such as demographic characteristics (e.g. density, age, gender, income, unemployment rate) and access to infrastructure or to ecosystem services.

While recognizing other human factors that contribute to exposure and vulnerability is crucial for comprehending how stressors escalate into impacts, challenges exist in measuring and assessing them. Comprehensive databases or inventories of impacts are country-dependent and are often incomplete. Information about employment rates, income levels, and industry-specific data is lacking. This kind of data is essential for understanding the economic vulnerabilities of different populations and regions. Moreover, data related to the quality of housing and infrastructure is also limited, which can significantly influence the ability of communities to withstand and recover from disasters. Additionally, knowledge about health insurance coverage and accessibility to medical services is limited, which affects disaster response and recovery. Understanding the societal aspects that influence vulnerability is also important. Data on traditional coping mechanisms and local adaptation practices that communities have historically employed can be limited too. Moreover, social norms, cultural practices, and beliefs play a significant role in shaping vulnerability (Kuhlicke et al., 2023). Inadequate data on internal and cross-border migration patterns limits the understanding of how population movements can be influenced or triggered by disasters.

*Impacts* are anomalous states of ecosystems or social systems compared to a reference state or variability range. They can be positive, negative or both at the same time. Moreover, the impacts themselves may span multiple dimensions, including economic losses, infrastructure damage, crop yield or plant productivity, as well as non-economic losses, such as impacts on human health, cultural, or biodiversity losses. Impacts can also cascade in society, between different sectors or different regions.

The added value of our proposed framework is that anthropogenic activities are not only included as an external forcing on hydro-climatic drivers, but also on the other factors leading to the impact, through socio-environmental

factors that can affect both the stressors and the impacts, for example through water or forest management, urban planning or agricultural policies. This corresponds to long-term adaptation policies. The framework can also include short-term response to an event (i.e. coping), either on stressors, such as sandbags to contain flooding or irrigation to prevent soil moisture drought, or directly on impacts, such as emergency response through e.g., humanitarian help, or population displacement.

The framework can be applied qualitatively and quantitatively, based on quantitative data, qualitative documents, and expert views.

## 3) Case studies

A qualitative version of this framework could be established quickly after a disaster, as part of a fast-track attribution study and could help to determine the relevant factors at play in a given event. This type of approach would be complementary to the efforts undertaken by initiatives such as World Weather Attribution (Philip et al., 2020), which have sought to add to their climate change attribution analysis a discussion on exposure and vulnerability. We believe that our approach places the contributions of climate change and drivers of vulnerability on a more equal footing. We illustrate this with case studies of the 2021-2022 drought in Kenya, the 2013-2015 marine heatwave in the northeast Pacific and the 2017 fires in Portugal.

The framework described in this article could also facilitate attribution studies that make a more comprehensive assessment of one or several causal relationships between human activities, socio-environmental factors, the climate and disasters. As such, the objective would not be to achieve a complete study of all the causal ramifications behind each weather-related disaster, but to start by focusing on some of the causal links that can be studied using quantitative models. In the other two case studies, we describe how this quantification could be envisioned with further research based on existing models and methods, with a focus on a subset of the causality chain. We present two case studies accounting for part of the anthropogenic activity on socio-environmental factors, with counterfactual based adaptation strategies: the Aqua alta in Venice with a simple economic model of losses, and the California drought with a model of reservoir water level. We chose a case study grounded in extreme attribution framing with the Acqua Alta case study to discuss how to get closer to impacts while exploring non-climatic counterfactuals. On the other hand, the California drought is grounded in a DRR approach, where we detail the use of an adaptation counterfactual and discuss options to add a climate change component to this kind of analysis.

We chose case studies of different types of events and different regions to illustrate the diversity of issues surrounding anthropogenic influence on climate-related disasters. These case studies are exploratory discussions and do not pretend to be full applications of the proposed framework.

a) Kenyan drought (2021-2022)

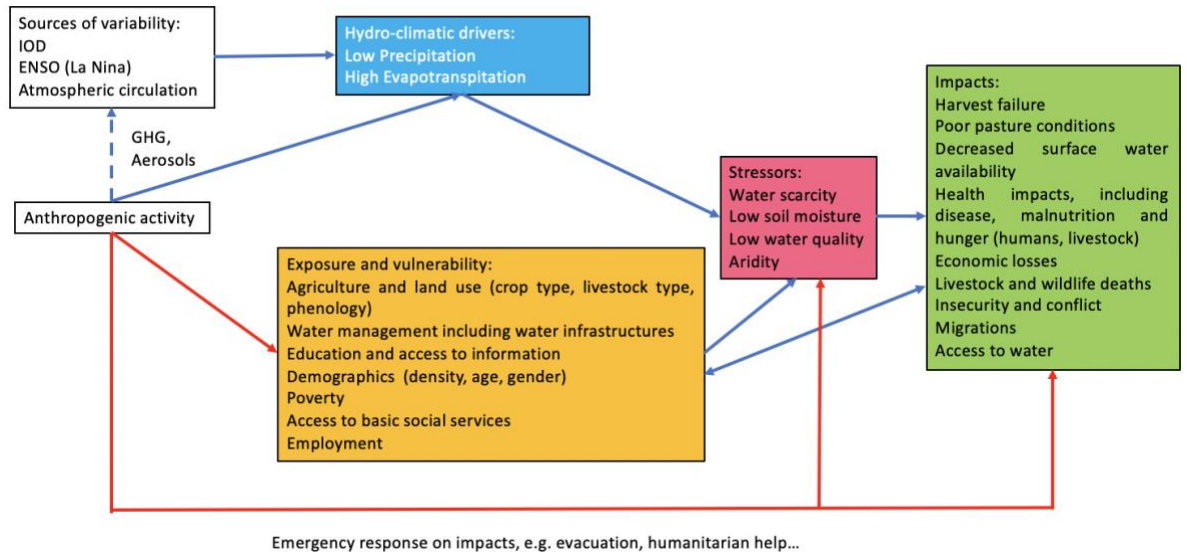



*Figure 2: Causality chart for the 2021-2022 Kenyan drought. This is a partial causality chart based on information collected from academic literature and reports, which are detailed in the text. A more complete chart could be established in partnerships developed with subject matter and local expertise.*

## The event and its impacts

For a period of 2 years, Kenya experienced an exceptional drought event that was considered the worst in 40 years (Kimutai et al., 2023). Over the period, persistent drought conditions led to substantial harvest failure, poor pasture conditions, livestock losses, decreased surface water availability, and fueled both human-wildlife and human conflicts and migration (including internal displacements) (WFP, 2022). The livelihoods of the agro-pastoralists were severely threatened with increased risk of disease, malnutrition, hunger and death (MPI, 2023). In September 2021, the Kenyan government declared a drought emergency (WFP, 2022). The drought situation remained critical (alert and alarm drought phases) until February 2023 in most arid and semi-arid counties with 4.35 million people in need of aid (NDMA, 2022). The number of livestock deaths rose to over 2.4 million and cases of acute malnutrition were reported among 942,000 children aged 6-59 months and 134,000 pregnant or lactating women (UN News, 2022). The government allocated a further Ksh. 4 Billion (approx. US$ 30 million) to the nation's drought alleviation programme

(Kenya Government, 2023) in February 2023. By that time close to 9,210 metric tonnes of food commodities had been distributed and Ksh. 1 Billion (approx. US$ 7.29 million) cash-based transfers had been made (World Food Programme (WFP), 2023). This list of impacts is summed up in the green box of Figure 2.

**Hydro-climatic drivers and attribution to anthropogenic climate change**

The hydro-climatic drivers of the drought are multiple, but at the first order, they can be described through precipitation and evapotranspiration (see blue box in Figure 2). Attribution analysis of rainfall trends and the combined effect of rainfall deficit with high temperatures in the Southern Horn of Africa covering parts of southern Ethiopia, southern Somalia, and eastern Kenya showed that anthropogenic influence on both rainfall and evapotranspiration increased the drought severity to "exceptional" (based on the US Drought Monitor classification (U.S. Drought Monitor)), whereas in the absence of climate change it would have been a normal drought (Kimutai et al., 2023). Kimutai et al. (2023) also found that in today's climate, dry conditions in the March-April-May rainfall season with a return period of 10 years have become twice as likely due to climate change. The drought years (2021-2022) have also been affected by internal variability, as they coincided with consecutive La Niña conditions which are associated with reduced rainfall over the region in the October-December (OND) season.

**Exposure and vulnerability**

Key stressors in this event were soil moisture, water scarcity or water quality (pink box of Figure 2). Lam et al. (2023) showed that soil moisture deficit and water scarcity are key elements determining differential drought impacts for different counties of Kenya. These indices are modulated by a variety of long-term environmental and socio-economic factors such as long-term aridity, poverty, lack of economic development, limited access to basic social services, low education levels, as well as water management, maintenance of the supply system, and the presence or absence of reservoirs. These human factors have been identified in reports (FEWS NET 2017, 2013), and documented by small-scale sociological studies (Adano et al., 2012; Quandt, 2021). For example, Nyberg et al. (2020) conducted interviews with smallholders in Western Kenya and found that money, knowledge and labour are key to understanding individuals' ability to cope with rainfall variability. Some similar studies could be done in the region affected by the 2021-2022 drought.

The impacts of droughts can also be mitigated by policies, coping strategies, early warning, early action, and timely response (Wens et al., 2022). As an example, the implementation of climate services based on seasonal forecasting to help local farmers make decisions regarding crop and livestock management could be an efficient adaptation measure to reduce the impacts of droughts (Busker et al., 2023). International aid also plays a role in building community resilience to drought (Kithikii, 2023), but focus on emergency response can also lead to long-term dependency (Ng and Yap, 2011).

A key problem with better accounting for exposure, vulnerability and the effect of human activities on drought stressors and impacts is that the existing datasets do not include granular local knowledge. For example, the global water scarcity dataset of McNally (2019) takes into account population density, but is blind to reservoirs and other water management systems or inefficiencies (Lam et al., 2023). Additionally, this dataset has also never been validated on the Horn of Africa. This means there is still a lot of work to be done to provide a comprehensive understanding of the way human activities influence drought impacts.

b) The 2013-2015 marine heatwave in the northeast Pacific

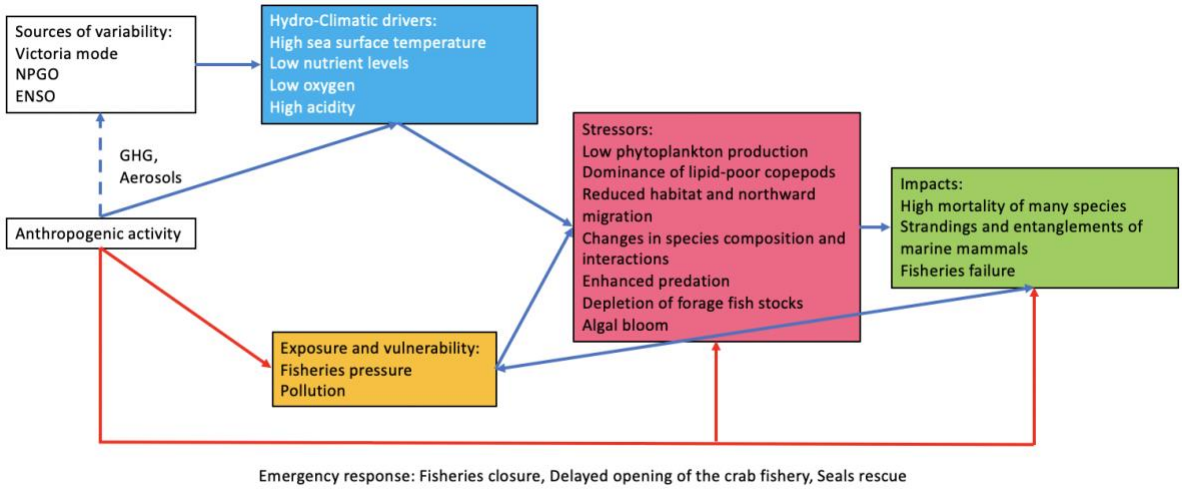



*Figure 3: Causality chart for the 2013-2015 Pacific marine heatwave. The references used to fill each box are listed in the text. This is a partial causality chart, based on the literature listed in the text. A more complete chart could be established in partnerships developed with subject matter and local expertise.*

## The event and its impacts.

Between 2013 and 2015, the northeast Pacific experienced the most intense and longest-lasting marine heatwave ever recorded, with maximum sea surface temperature (SST) anomalies of more than 5°C lasting for more than 350 days

(Di Lorenzo and Mantua, 2016; Laufkötter et al., 2020). The record-breaking marine heatwave, referred to as the 'Blob', had unprecedented impacts on marine ecosystems and the societies relying upon them. Ecological impacts included increased mortality of many marine species, which resulted from a combination of stressors, all listed in the pink box in Figure 3. First, low phytoplankton productivity (Le Grix et al., 2021; Whitney, 2015; Wyatt et al., 2022) caused significant changes in zooplankton and marine invertebrate populations (Leising, 2016), with many species shifting their distributions toward higher latitudes (Cavole et al., 2016; Cheung and Frölicher, 2020). Second, an increased proportion of less nutritious warm-water copepods in the north-eastern Pacific reduced prey energy content for forage fish, while the heatwave enhanced the metabolism and thus food demand of predators, thereby depleting forage fish stocks. Third, the heatwave also triggered an unprecedented harmful algal bloom off the U.S. west coast, which, in combination with changing prey dynamics, amplified the heatwave's impacts on sea-birds and mammal species (Cavole et al., 2016; Jones et al., 2018; Piatt et al., 2020). Mass strandings of whales in the Gulf of Alaska and sea lions in California were reported during the Blob. Toxins produced by the algae also contaminated shellfish and prompted the prolonged closure of valuable shellfish fisheries. Economically, the 'Blob' led to millions of dollars in losses among fishing industries. Shellfish fisheries incurred estimated losses of $48 million (Cavole et al., 2016). These impacts are listed in the green box of Figure 3.

**Hydro-climatic drivers and attribution to anthropogenic climate change**

In this case, the main hydroclimatic proxy is the high SST. The unprecedented heatwave primarily resulted from natural climatic variability. Bond et al. (2015) attributed the development of the 'Blob' to an unusually strong and persistent weather pattern, featuring sea level pressure much higher than normal over the Gulf of Alaska. These sea level pressure anomalies were forced from the atmosphere by the North Pacific Oscillation (Tseng et al., 2017). Reduced circulation in the North Pacific Subtropical Gyre suppressed the heat loss from the ocean to the atmosphere and caused relatively weak cold advection in the upper ocean (Leising, 2016). The resulting warming in the northeast Pacific is characteristic of the second mode of SST variability in the North Pacific, the Victoria Mode, thought to have acted as a precursor to the development of the 2015/16 El Niño (Di Lorenzo and Mantua, 2016), which further enhanced the 'Blob' (Tseng et al., 2017).

The 'Blob' was a compound extreme event; it combined extreme temperatures with anomalies in multiple ocean ecosystem metrics, such as low

oxygen and nutrient levels, which we also classify here as hydroclimatic drivers of the event (Gruber et al., 2021; Le Grix et al., 2021; Mogen et al., 2022). The severity of the Blob's impacts is partly explained by these anomalies, to which human-driven climate change possibly contributed. First, without climate change, the Blob may have been less intense and long-lasting. Long-term ocean surface warming has caused longer and more frequent marine heatwaves over the past century (Frölicher et al., 2018; Oliver et al., 2018). Laufkötter et al. (2020) attribute the long duration and high intensity of the Blob to human-induced ocean warming. Furthermore, climate change has also been associated with ocean deoxygenation, which compresses marine species' habitats, acidification, and lower nutrient levels over certain regions (e.g. Bopp et al., 2013).

**Exposure and vulnerability**

Human activities modulate exposure and vulnerability (see yellow box of Figure 3) and can directly influence both the stressors and the impacts of the event. As an example of the former, pollutants emitted by industries may fertilise coastal waters and facilitate the onset of harmful algal blooms, although, to our knowledge, no link has been established between coastal pollution and the harmful algal bloom that occurred during the Blob. The opening of the crab fishing season was delayed until late March 2016 due to unsafe toxin levels (Santora et al., 2020). This prevented food poisoning, but affected sales and job security in the crab industry. There is a lack of studies regarding the way this event interacted with social vulnerability, and the type of populations who suffered from these changes, both within fisher communities and the people relying on crabs for food consumption.

In addition, while crab fishing activity is usually highest in November and December, the reopening of the season in spring 2016 coincided with the arrival of migrating whales off California. The delayed season resulted in record entanglements of whales in crab fishing gear. Cooperation between fisheries, resource managers, and scientists is necessary to develop more efficient mitigating strategies (Gissi et al., 2019; Hazen, 2018). Catch limits must also be adapted to species migration during marine heatwaves, e.g. raised when a species population is growing and lowered when it is declining. Permits to target a more diverse portfolio of species may also be delivered to fishers during heatwaves, so they can better pivot toward a species that is abundant.

c) Extreme fire season of 2017 in Portugal

## The event and its impacts

The year 2017 was one of the worst fire seasons recorded in Europe, with over 1.2 million ha burned, and it directly killed at least 127 persons in the European Union (European Commission et al., 2018). Of these, 540 thousand ha and 114 fatalities occurred in Portugal, mostly due to two mega-fire events in central Portugal, one in June and another in October 2017, months which were not considered in the official definition of critical fire season by the Portuguese authorities. The 2017 wildfires in Portugal resulted in major forest biomass losses, and damages to agriculture, buildings and other infrastructure, totalling 1.2 billion USD in economic losses and insurance costs of 295 million USD (Ramos et al., 2023).

While both events were exceptional, here we focus on the event occurring between 15 and 16 of October, in which over 200 thousand ha were burned, most of them in under 24h (Castellnou et al., 2018), and 51 people died (Rodrigues et al., 2022). The mega-fires generated a smoke plume that raised particulate matter concentrations in the atmosphere above safe levels, resulting in an increase in hospital admissions due to asthma and other respiratory diseases in Portugal (Oliveira et al., 2020). Figure 4 shows the different hydro-climatic drivers, elements of exposure and vulnerability and stressors contributing to these impacts.

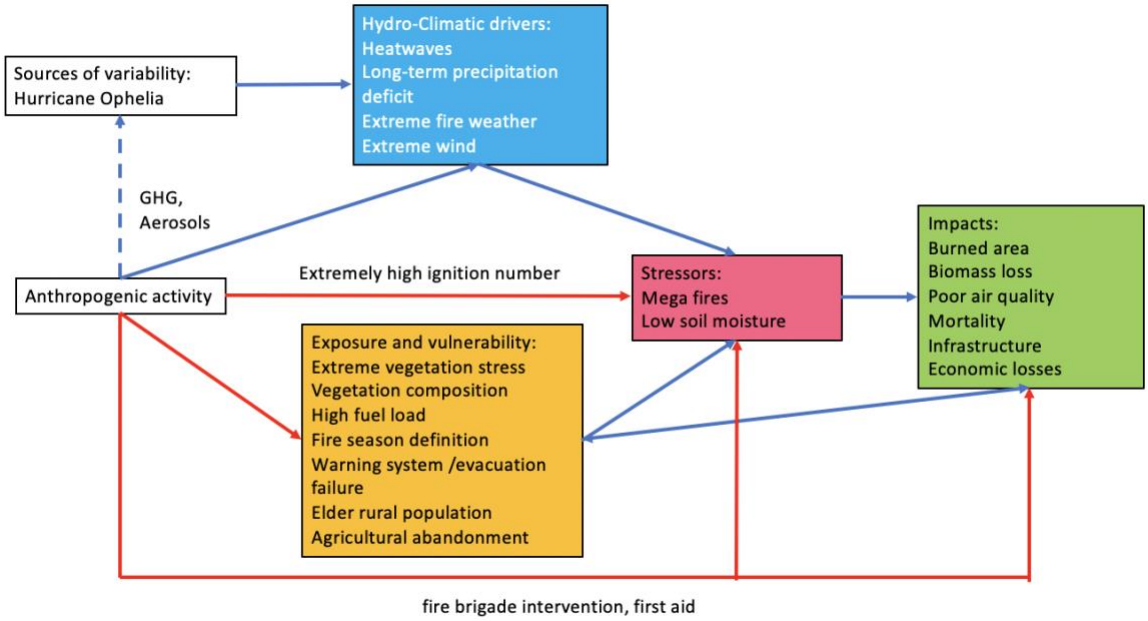



*Figure 4: Partial causality chart for the October 17 fires in Portugal, based on Ramos et al. (2023), and additional studies including additional socio-environmental factors listed in the text. A more complete chart could be established in partnerships developed with subject matter and local expertise.*

Ramos et al. (2023) analysed this compound event following a storyline approach. They based their analysis on a commonly used fire risk model, the Canadian Forest Fire Weather Index System (CFFWIS) to decompose the event into the most relevant components of the "fire triangle": hydroclimatic drivers, fuel characteristics, and ignitions. Their analysis does not assess the way anthropogenic climate change modulated the event, but we discuss how it could be done below. It is also qualitative in nature, but detailed enough that it could be used as a canvas for more quantitative protocols. Such protocols could in principle be implemented by land surface models that simulate burned area prognostically, based on fire weather, fuel dynamics and ignitions (Jones et al., 2022), for which counterfactuals could be built. Including interactions with human activities is more challenging, although first attempts to develop such models exist (Perkins et al., 2024).

Each of the elements of the fire triangle was associated with exceptional conditions that compounded on October 15$^{th}$, as described below.

**Hydro-climatic drivers and role of anthropogenic climate change**

The passage of Hurricane Ophelia along the Iberian Peninsula coast is considered a key element in the development of this fire event. Ophelia developed in early October in the central North Atlantic basin and, moving in a north-eastward direction from October 12$^{th}$ onwards, transitioned to an extratropical storm. On October 15$^{th}$ Ophelia was close to the coast of the Iberian Peninsula and promoted the advection of extremely hot and dry air from Northern Africa, with near-surface temperature reaching over 30$^{o}$C and relative humidity below 20% over most of the Portuguese territory (Ramos et al., 2023). Ophelia was the easternmost major hurricane on record in the Atlantic and its passage sustained very strong wind speeds, especially in central Portugal where fires occurred (maximum wind speed between 50-80km/h). These three exceptional hydrometeorological conditions implied a high propensity of fires to spread, once ignited.

In Ramos et al. (2023) no storm-specific attribution statement was made. A quantitative application of our framework to this event would require a formal attribution study on at least one or several of the hydroclimatic drivers of the event. This attribution could be conditional to the circulation (e.g. using the same methodology as Faranda et al., 2023), or unconditional (e.g. Philip et al., 2020).

Turco et al. (2019) have already shown that the climate change signal would have led to larger burned areas for the 2017 fire season over Portugal (not restricted to the October event), in the absence of other drivers. It thus appears reasonable to hypothesize (although no specific attribution analysis has been

conducted to our knowledge) that climate change may have contributed to increasing the heat and atmospheric dryness advected by Ophelia (López et al., 2021). The highly active 2017 Atlantic hurricane season as a whole, with six major storms, has been traced to unusually warm North Atlantic tropical SSTs (Murakami, 2018), a warming that is projected to increase further. In general, tropical cyclones have become more intense in the North Atlantic, which is unlikely to be explained by natural variability alone (Seneviratne et al., 2021), and tropical cyclones are projected to further intensify due to anthropogenic forcing (Seneviratne et al., 2021).

## Exposure, vulnerability, and human influence

*Fuel characteristics*

This exceptional fire event was preconditioned by extremely high levels of vegetation stress associated with the prolonged drought conditions that had started in July 2016. Remote sensing data indicated strong vegetation browning from August to October 2017 (Ramos et al., 2023), which implies very dry – and easily flammable – fuel. Indeed, the moisture content of fine fuels was estimated at 3-6% (Castellnou et al., 2018). Moreover, forests dominated by highly flammable tree species (*Pinus Pinaster*) comprised the majority of the burned area, most of which had not burned in the previous 19 years, therefore likely to hold high fuel load (Castellnou et al., 2018).

In the Mediterranean, there is a high confidence in the increase in frequency and severity of hydrometeorological droughts, and medium confidence for soil moisture and ecological droughts in the historical period. There is medium confidence that these signals can be attributed to anthropogenic climate change (Seneviratne et al., 2021). There is, however, low confidence in trends and attribution of meteorological droughts (Seneviratne et al., 2021). This difference highlights the role of increased evaporative demand, rather than precipitation deficits, in driving the observed increases in hydrometeorological, ecological and soil moisture droughts. Furthermore, increased evaporative demand due to warming trends results in *more severe* droughts in the Mediterranean (Vicente-Serrano et al., 2014), influencing fuel buildup and dryness. However, a separate attribution of climate change on fuel characteristics has not been done. This attribution is complicated by multiple ecological and other human influences on fuel dynamics (e.g. elevated $CO_2$ and land-use change), as illustrated by Bastos et al. (2023) using a storyline approach. A simple model of the total seasonal burnt area over Portugal (thus *not* restricted to fuel characteristics or the October events) indicated that temperature and dryness variability are statistically moderately predictive, and without the historical trends in

temperature and dryness, the 2017 fire season would have been much less severe (Turco et al., 2019).

*Ignitions*

The critical fire season considered by the Portuguese authorities was typically considered between July and September. The critical period was prolonged until November 23rd, which imposed a prohibition of management fires in forest and agricultural areas (European Commission et al., 2018). This is, however, a time of the year when fire is commonly used in local agricultural management practices. On October 15th, an extremely high number of ignitions was registered (over 500 in a single day), partly attributed to the fact that rain had been forecasted for the next day (Ramos et al., 2023).

The combination of high wind speeds, exceptionally dry fuel and the extremely high number of ignitions led to the development of multiple mega-fires progressing at very high speeds, with over 10000 ha burned per hour between 4pm and 5am of the next day (Castellnou et al., 2018). Some of the most intense fires developed into pyroconvection events that further intensified strong winds and contributed to unpredictable and long-distance fire spread (Castellnou et al., 2018). These pyroconvective events were the largest reported until then in Europe, and the largest globally in that year (Gomes Da Costa et al., 2020). All these elements made fires very difficult to fight and exceeded the response capacity of the Portuguese Civil Protection authorities (Viegas et al., 2019), leading to major losses of infrastructure and human lives.

Adding to the specific drivers of this event, additional socio-environmental factors contributed to the observed impacts. While being relatively small, Portugal is the country with the highest values of annual burned area in the European Union (Gomes Da Costa et al., 2020), with 97 thousand ha/year on average in the period 2006-2020 (EFFIS, 2024). It is recognized that the predominance of such large and frequent fires in Portugal is explained not only by the occurrence of favourable fire weather conditions, but also by territorial and landscape planning policies (e.g., land ownership), and land-use and demographic changes (e.g. rural abandonment and expansion of the wildland-urban interface) that result in a large extent of poorly managed forests and shrublands, which facilitate the occurrence of very large and uncontrollable fires (Barros and Pereira, 2014; Benali et al., 2021; Fernandes et al., 2016).

Additionally, underlying socio-environmental factors are likely to have contributed to the high mortality rates. The Portuguese territory is characterised

by small villages dispersed in the forested landscape. Traditionally, rural populations protected their villages from fires with surrounding agricultural fields, but rural abandonment and aging of the rural population have led the forest-urban interface closer to rural populations (Rodrigues et al., 2022). The elderly population in rural areas is especially vulnerable due to reduced mobility and a potential underestimation of the fire risks under the new landscape characteristics. In the case of the October 2017 fires, the majority of the victims were rural inhabitants over 50 years old, many with health and mobility limitations, who were taken by surprise in their homes (Rodrigues et al., 2022). Adding to this, no preemptive evacuation measures were carried out by the Portuguese Civil Protection authorities (Rodrigues et al., 2022), possibly because of the fast-developing and to some extent surprising nature of the hydro-meteorological compound event described above. One of the key issues with potential quantitative frameworks based on a land-surface model would be to integrate these aspects of social vulnerability to the risk of fire and total burned areas.

d) Attribution of Acqua Alta events and evaluation of adaptation strategies

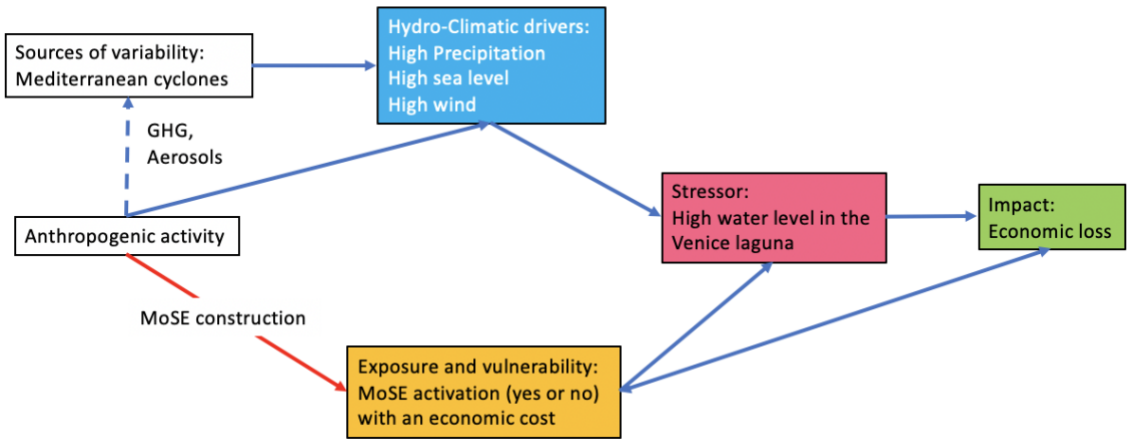



*Figure 5: Partial causality chart for the Acqua Alta Events in Venice modulated by the activation of the MoSE, describing the protocol used by Faranda et al (2023). Many impacts and most of the exposure and vulnerability are not addressed in this study.*

## The event and its impacts

Coastal cities, such as Venice, are confronted with escalating climate extremes that test their urban resilience (Tebaldi et al., 2021). Among these challenges,

the prominent issue of flooding stands out, with “Acqua Alta events” describing an exceptionally high tide peak. Acqua Alta events in Venice are primarily triggered by intense extratropical cyclones around the Adriatic Sea, making them a significant concern (Bevacqua et al., 2017; Umgiesser et al., 2021). The rising sea levels caused by human-induced climate change further compound the vulnerability of coastal cities to extratropical cyclones, underscoring the urgency of adaptive measures. Here, we focus on one of those adaptive measures: the Experimental Electromechanical Module (MoSE), an ensemble of mobile barriers that can be activated to mitigate the influx of seawater in the city, in a changing climate. Faranda et al. (2023) attributed the extreme water level in Venice during Acqua Alta events, as well as their economic cost for the city to both the influence of anthropogenic climate change on the weather patterns responsible for those events and the activation of the MoSE. Here, we show how their results can be interpreted to produce a more holistic understanding of the human contribution to impacts through anthropogenic climate change and a technical adaptation strategy, using our framework.

**Hydro-climatic drivers and role of anthropogenic climate change**

This study focuses on four high-impact Acqua Alta incidents — 1966, 2008, 2018, and 2019 — that flooded Venice. These events occurred during increased Mediterranean cyclone activity, leading to damage to infrastructure and historical heritage. The complex interplay between these climatic events and the intricate geography of the Venetian lagoon highlights the dynamics of Acqua Alta. Mediterranean cyclones, resulting from interactions between Atlantic low-pressure systems and the Mediterranean Sea, draw energy from the warm basin waters (Lionello et al., 2021). These cyclones intensify Acqua Alta through the convergence of winds and associated storm surge towards the northern Adriatic Sea coast, as well as through higher water levels due to the lowered sea level pressure (barometric pressure effect) (Bevacqua et al., 2017). The synergy between these cyclones and the Adriatic's geographic features magnifies their impact on Venice (Zanchettin et al., 2021).

To attribute Acqua Alta events, Faranda et al. (2023) employed analogues of atmospheric patterns (Faranda et al., 2022). The study selects distinct periods - [1950-1979], the counterfactual with a lesser influence of anthropogenic climate change, and [1993-2022], the factual with current level of anthropogenic climate change, and identifies analogous atmospheric situations for the four events in both periods. This allows the authors to assess both the change in key variables describing hydroclimatic drivers such as wind and precipitation for similar types of circulation, and the quality of analogues in both periods, i.e.

whether this type of weather pattern's frequency is changing. They also used the sea level data in the Venice laguna (stressor) at the dates of the analogues for both periods to assess the change in sea level and relate it to climate change. With this method both the effect of sea level rise and of changes of weather-related variables are taken into account. An exponential model, based on limited existing data, is used to derive damage based on sea level in Venice. For the 1966 Acqua Alta event they estimated both sea level and damages for both the counterfactual and factual worlds with large uncertainties: 122 cm (uncertainty interval 116-189) and 0.13 (0.09-1800) million euros for the counterfactual world, and 123 cm (107-156) and 0.45 (0.06-28) for the factual world (according to Table 1 of Faranda et al., 2023).

**Human influence on exposure: the MoSE as an adaptation policy**

In this study, the exposure and vulnerability components are limited to the activation (or not) of the MoSE, which does not account for any aspects of social vulnerability. As the MoSE has been activated 40 times since its operationalization in 2019, the authors can evaluate the decrease of sea level in Venice subsequent to its activation. To assess the MoSE system's effectiveness, the study uses sea level data from Punta della Salute (inside the lagoon) and Piattaforma (outside the lagoon) stations to construct two damage statistics. One uses Punta della Salute's MoSE values, while the other employs counterfactual Piattaforma values. This approach factors in Piattaforma's location and feeds it to the damage models.

Faranda et al. (2023) built a new counterfactual world that corresponds to the factual world with the current climate, 1993-2022 in their study, with the MoSE activated. Additionally, when analysing MoSE-activated statistics, the study substitutes damages with the daily operational cost of MoSE. The authors found that MoSE proves effective against three of the four events—1966, 2008, and 2019—highlighting its adaptability (see Table 1 and Figure 3 of Faranda et al., 2023). For the 1966 event, they estimated that the MoSE decreased the sea level to 111cm (59-156) with a cost of 0.25 (0.07-28) millions of euros.

This study however presents some limitations. While it covers both a part of climate change influence on weather extremes that can lead to Acqua Alta and one potential adaptation strategy, key factors like land subsidence, tidal effects, local precipitation, river discharge, local influences on flooding susceptibility, as well as social vulnerability, including the differentiated impacts the building and activation of the MoSE may have on different populations, are not fully considered. The interaction between land subsidence, climate-induced sea

level rise, and other local dynamics necessitates comprehensive analysis beyond this study's scope (Ferrarin et al., 2022). Many counterfactual worlds would have to be designed to better encompass human factors. Another limitation of this study is its focus on a single technical solution for adaptation, without exploring other options, which could be nature-based (Sudmeier-Rieux et al., 2021) or human-centered (Hore Katherine et al., 2020; Lewis and Kelman, 2012).

e) The 2020 California drought and the FIRO system

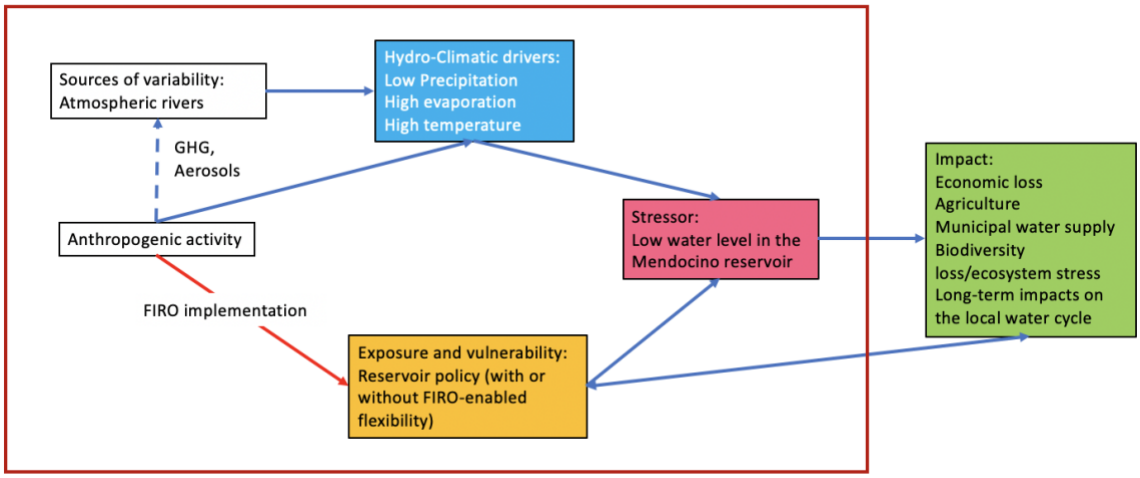



*Figure 6: Partial causality chart for the 2020 California drought modulated by the use of the FIRO system. Here, we only discuss how to achieve a quantitative attribution of stressors, not impacts, and the causality chains inside the red box. Many impacts and most of the exposure and vulnerability are not addressed in this study.*

**The event and its impacts**

Since 2010, California has had two major drought events: in 2012-2016 and more recently in 2020-2022. From 2012 to 2016, California experienced one of its deepest, longest, and warmest droughts in history, with a return period estimated at one in 1,200 years (Lund et al., 2018). The 2012-2016 drought was responsible for a reduction in snowpack and streamflow leading to vegetation stress and a deficit in hydroelectric power production, wildfires, and water shortages for rural drinking water supplies, agriculture, and cities. Overall, the drought caused billions of dollars in economic losses (Lund et al., 2018). More recently, the three-year period that started in 2020 was among the driest and hottest in California since 1895 (Medellín-Azuara, 2022). In addition, low precipitation and above-normal temperatures resulted in higher evapotranspiration, which decreased water availability and increased the water

demand from agriculture, ecosystems and communities (Medellín-Azuara, 2022). The reduction in crop production during these 3 years of drought caused gross farm revenue losses estimated at $3 billion. The food industry also incurred large impacts with revenues declining by 7.8% and an estimated 12,000 agricultural jobs lost in 2022 (Medellín-Azuara, 2022).

In this context, several measures of adaptation were proposed or introduced during the 2012-2016 drought (e.g. Delaney et al., 2020; Flint et al., 2018). In this case study we focus on how one of those adaptation measures applied to a subsequent drought from 2020-2022 affected water withdrawals and use, with a focus on 2020.

**Hydro-climatic drivers and role of anthropogenic climate change**

Both droughts developed due to a precipitation deficit, one of the main hydroclimatic drivers in this case, amplified by the gradual background warming from anthropogenic climate forcing, thus implicating anthropogenic climate change as a driver of increased drought risk in the region (e.g. Williams, 2020; Williams et al., 2015; Diffenbaugh et al., 2015; Swain et al., 2014). Mediterranean climates, like that found in the western U.S. state of California, are sensitive to droughts caused by hot and dry conditions (e.g. Cheng et al., 2016; Diffenbaugh et al., 2015). Although California's climate is inherently variable, recently California has been experiencing increasing hydrological extremes, including droughts (DeFlorio et al., 2024). The severity of these extremes is predicted to increase with climate change, with high uncertainties on the average precipitation trends (Bevacqua et al., 2022; Gershunov et al., 2019, 2017; Swain et al., 2018).

While there have been a few EEA studies on different subperiods of the 2012-2016 drought, with mixed results depending on how the attribution question was framed and which models were used (e.g. Diffenbaugh et al., 2015; Funk et al., 2014; Shukla et al., 2015; Wang et al., 2017; Lehner et al., 2018). A NOAA report concluded that the precipitation deficit during the 2020-2021 drought "appears to have been largely due to natural, but unfavourable, variations in the atmosphere and ocean" (Mankin et al., 2021). Hoell (2022) however found at a larger scale that climate change has increased the risk for the record low American Southwest precipitation in June-September 2020, with low confidence due to model biases and no significant observed trends. Seager et al. (2022) also concluded about the 2020 drought that "there is also evidence that the southern part of the region in spring is drying due to human-driven climate change", but this statement refers to the desert southwest, rather than Northern California rainfall which controls most of California's water availability.

In addition, Paciorek and Wehner (2024) found that the significance of observed drying trends in the southwest is likely overstated, highlighting the difficulty to distinguish any trends in California meteorological drought from natural variability. New studies related to the "pattern effect", however, suggest that anthropogenic forcing has at least contributed to the recent precipitation decline over the Southwest (Kuo et al., 2023).

However, precipitation may not be the best proxy to evaluate the influence of climate change on California droughts. Seager et al (2015) concluded for the 2011-2014 California drought "a long-term warming trend likely contributed to surface moisture deficits during the drought". In other words, while there is no clear influence of climate change on meteorological drought, the influence on agricultural drought is significant due to increases in evapotranspiration in a warmer climate. Presumably, this leads to increases in hydrological drought as runoff is lower when soils are drier and have more capacity to store incoming precipitation (Sumargo et al., 2021).

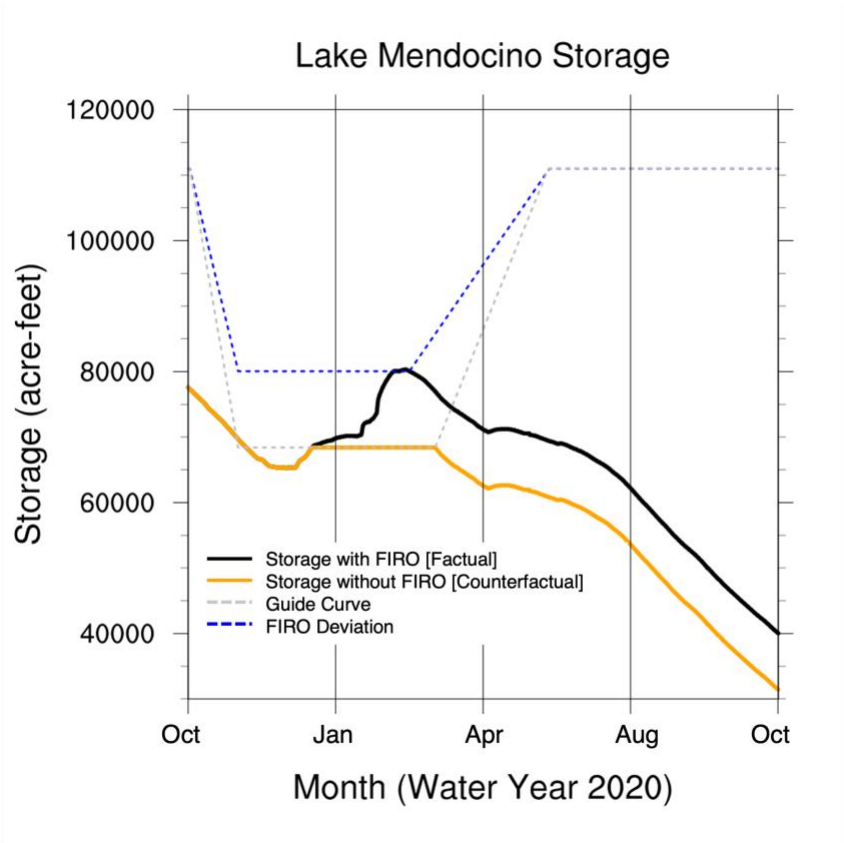
**Human influence on exposure: the FIRO program as an adaptation policy**

The Forecast Informed Reservoir Operations (FIRO) program was first conceived during the 2012-2016 drought. In response, Federal, State and local agencies initiated a Research and Operations Partnership with the University of California to investigate the viability of using forecasts to enable more efficient use of available storage. The pilot project was Lake Mendocino, a reservoir with a maximum storage of 111,000 acre-feet in the upper Russian River watershed in coastal northern California. The overarching goal of FIRO at Lake Mendocino is to apply forecasting advances to increase water supply reliability without reducing—and even potentially enhancing—flood protection capacity and downstream flows for ecosystem services (Wilson et al., 2022). The main strategy in terms of the forecast was to evaluate and improve the understanding and prediction of atmospheric rivers (Ralph et al., 2020), since these features contribute up to 50% of the state's annual precipitation (Dettinger et al., 2011).

In this case study, we focus on the adaptation, enabled by the viability assessment (Jasperse et al., 2020), of adding flexibility to reservoir operating procedures to increase water availability, thereby building an adaptation counterfactual. The stressor is the water level in Lake Mendocino (Figure 6). We present two versions of the water storage levels in the first FIRO pilot reservoir, one with the extra storage enabled by FIRO (factual) and another with the reservoir being managed to its previously mandated storage limits (counterfactual). To construct the counterfactual, we limit the storage to the

mandated level during the cool season when water input is provided from atmospheric rivers. We do not attempt to reproduce the periods when the reservoir would have gone above the mandated storage level until it was safe to release water downstream. When the mandated storage level begins to rise, we calculate the water level based on the prior water level in the counterfactual, and then the change (plus or minus) of the observed storage. Through investigating both scenarios, we quantify the tangible benefit of FIRO as an adaptation strategy against the ever-increasing water availability challenges in California.

*Figure 7: Storage and guide curves for Lake Mendocino during Water Year 2020, illustrating the factual (actual storage using the FIRO-enabled deviation (blue dashed line)) in the black curve, and the counterfactual (storage if the*




*reservoir had been managed to the existing guide curve (grey dashed line)) in the orange curve.*

In the case of Lake Mendocino, FIRO provides better water availability outcomes in both drought years and flood years as well as additional flood protection. The water saved through the use of a major deviation, requested as a result of the positive FIRO viability assessment, was close to 20% in water year 2020 (Fig 6).

Based on these first results, such a model could be used to compare Lake Mendocino storage, with and without FIRO (as shown here), and with and without climate change. In order to do so, a counterfactual world with reduced greenhouse gases and aerosol emissions could generate counterfactual temperature, precipitation and evaporation that could be translated into streamflows, to test if there is a significant change in inflows to Lake Mendocino related to climate change. Counterfactual worlds with higher concentrations of greenhouse gases could also be tested to assess whether the FIRO system will be robust to higher warming. These tests could be done using the framework we described here with synthetic forecasts as described in Brodeur et al. (2024). This type of approach is symmetric to the one described in the previous case study, as it would build on an approach tailored to compare worlds with and

without an adaptation measure and add the anthropogenic climate change component. A limit is that it still covers only a small techno-centric part of adaptation options and does not take into account social and environmental vulnerabilities (Hore et al., 2020; Lewis and Kelman, 2012).

## 4) Discussion

The case studies detailed above show several directions in which our framework could be used to expand extreme event attribution. We hope that this framework could help to shed light on shifting spaces for action in disaster risk reduction through the exploration of different causal drivers corresponding to different adaptation strategies to prevent the most adverse impacts of extreme weather events. It could also help to disentangle better how the non-stationarity of climate change interacts with the non-stationarity of vulnerability and exposure to modify the impacts of extreme weather events.

While this framework is promising, it is also ambitious as it is accompanied by three main limitations (which, however, also apply to any study of climate impacts). The first limitation is the lack of observed impact, vulnerability, exposure, and adaptation data. The availability of this data is typically not homogeneous in space and time, and is often not free to access, or is held under confidentiality clauses. Data limitations are particularly problematic in most vulnerable countries and for some health data such as mortality or hospitalisation data. Ongoing data collection and availability of vulnerability, exposure, adaptation and impact data in socio-economic and socio-ecological systems is thus of crucial importance. There is also a potentially large opportunity to tap into Earth observation data to assess exposure to support attribution, for example night-light data (Ceola et al., 2014).

The second hurdle is the readiness of impact models and how much we can rely on them to test the effect of different counterfactuals on impacts. Available process-based impact models could be used for this purpose. It is noteworthy that so far, the attribution part of the ISIMIP project – a flagship project of impact attribution – focuses on the attribution to climate change only (Mengel et al., 2021). Provided large enough datasets, quantification could also be achieved through the application of causal theory, for example using graphical models for causal discovery (Ebert-Uphoff and Deng, 2012).

The case studies on the Acqua Alta and on the FIRO system suggest that simple models can evaluate the influence of two different adaptation strategies on the water level in Venice during a flood and on the water level in the Mendocino reservoir during a drought, with suggestions on how to also include counterfactual events not affected by climate change. The models however explore technological adaptation options. Including social vulnerability metrics, the distribution of inequalities, the spatial distribution of sociodemographic segments of the population, and evaluating the effect of public policies on the way some population segments disproportionately suffer from impactful events would require different databases and more complex models. Agent-based models, for example, have been used to differentiate effects of climate change and different policies on people's adaptation behaviour and impacts in scenario analysis (e.g. Wens et al., 2021), but they could equally well be applied for event attribution.

The third issue is the definition of pertinent factual and counterfactual worlds. While the counterfactual is straightforward in the case of specific adaptation systems as the ones described in two of our case studies, it is more challenging to evaluate potential maladaptation. For example, while it is possible to use a coupled vegetation model to evaluate the influence of the choice of crops on crop yield during droughts or of the choice of trees on burned areas, the choice of the relevant type of crops or trees to test is more subjective. Another challenge for the definition of counterfactuals stems from the complexity of the possibly many interactions between drivers, exposure, vulnerability and stressors. For example, climate change, elevated $CO_2$ and land use all contribute to fuel changes. A way to proceed could be to define these counterfactuals in partnership with involved stakeholders depending on which levers of action they would like to explore. Defining pertinent counterfactuals will be key to make the findings of studies using our framework policy-relevant and help to build scientifically informed adaptation policies.

We acknowledge that the attribution of disasters is complex and that it has moral and political consequences, as it may be used as a way to attribute responsibilities (Lahsen and Ribot, 2022). There is no "one frame fits all" to those problems, and the frame presented here might also participate in inadvertently concealing some aspects leading to disasters, since we can only explore a limited number of counterfactual worlds and focus on a limited number of causes of the disasters. However, we believe that our proposed approach would address the limitations of EEA pointed out by Lahsen and Ribot (2022),

Hulme et al. (2014; 2011), and Olsson et al. (2022), especially for studies that are heavily publicised in general media, and picked up by decision-makers.

It is important to recognize that the type of scientific products we deploy as scientists can serve multiple political agendas. Because EEA has been thought of as a branch of science to inform society, it is paramount to acknowledge the ethical and political ramifications of advertising this type of scientific product as a key to provide climate justice. While climate-centric attribution might be helpful in some contexts to unveil the changes in the distribution and intensity of extreme hazards, and to highlight the inequalities between vulnerable countries not responsible for the emissions and historical emitters, it might end up hampering vulnerability reduction in others, which has been shown to be a crucial driver to reduce impacts (e.g. Kreibich et al., 2017b for floods). EEA cannot be thought of as a depoliticizing tool (Allen, 2003; Hulme et al., 2011; Olsson et al., 2022), as it might be used as a political tool to shift the debate towards hazard-driven disaster risk reduction. Paradoxically, by pushing for a climate justice agenda, extreme event attribution might participate in strengthening the focus on the hazard part of disasters and be blind to long time social conflitcts surrounding disaster reduction to focus disaster risk reduction around social vulnerabilities (Grant et al., 2015; Hulme et al., 2011; Lahsen and Ribot, 2022).

We hope that the framework proposed in this paper can help to start bridging the gap between the EEA and the DRR communities. This will require interdisciplinary work between experts in climate attribution and experts in attribution of catastrophes to other human activities.

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## References

Abram, N.J., 2021. Connections of climate change and variability to large and extreme forest fires in southeast Australia. Commun Earth Env. 2, 8.

Adano, W.R., Dietz, T., Witsenburg, K., Zaal, F., 2012. Climate change, violent conflict and local institutions in Kenya's drylands. J. Peace Res. 49, 65–80. https://doi.org/10.1177/0022343311427344

AghaKouchak, A., Feldman, D., Hoerling, M., Huxman, T., Lund, J., 2015. Water and climate: Recognize anthropogenic drought. Nature 524, 409–411. https://doi.org/10.1038/524409a

AghaKouchak, A., Mirchi, A., Madani, K., Di Baldassarre, G., Nazemi, A., Alborzi, A., Anjileli, H., Azarderakhsh, M., Chiang, F., Hassanzadeh, E., Huning, L.S., Mallakpour, I., Martinez, A., Mazdiyasni, O., Moftakhari, H., Norouzi, H., Sadegh, M., Sadeqi, D., Van Loon, A.F., Wanders, N., 2021. Anthropogenic Drought: Definition, Challenges, and Opportunities. Rev. Geophys. 59, e2019RG000683. https://doi.org/10.1029/2019RG000683

Allen, M., 2003. Liability for climate change. Nature 421, 891–892. https://doi.org/10.1038/421891a

Ashraf, S., Nazemi, A., AghaKouchak, A., 2021. Anthropogenic drought dominates groundwater depletion in Iran. Sci. Rep. 11, 9135. https://doi.org/10.1038/s41598-021-88522-y

Authority (NDMA), N.D.M., 2022. Resource Document.

Barros, A.M.G., Pereira, J.M.C., 2014. Wildfire Selectivity for Land Cover Type: Does Size Matter? PLOS ONE 9, e84760. https://doi.org/10.1371/journal.pone.0084760

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, eaba2724. https://doi.org/10.1126/sciadv.aba2724

Bastos, A., Sippel, S., Frank, D., Mahecha, M.D., Zaehle, S., Zscheischler, J., Reichstein, M., 2023. A joint framework for studying compound ecoclimatic events. Nat. Rev. Earth Environ. 4, 333–350. https://doi.org/10.1038/s43017-023-00410-3

Benali, A., Sá, A.C.L., Pinho, J., Fernandes, P.M., Pereira, J.M.C., 2021. Understanding the Impact of Different Landscape-Level Fuel Management Strategies on Wildfire Hazard in Central Portugal. Forests 12. https://doi.org/10.3390/f12050522

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, 2701-2723,. https://doi.org/10.5194/hess-21-2701-2017
Bevacqua, E., Zappa, G., Lehner, F., 2022. Precipitation trends determine future occurrences of compound hot–dry events. Nat Clim Chang 12, 350–355. https://doi.org/10.1038/s41558-022-01309-5
Blauhut, V., 2020. The triple complexity of drought risk analysis and its visualisation via mapping: a review across scales and sectors. Earth-Sci. Rev. 210, 103345. https://doi.org/10.1016/j.earscirev.2020.103345
Bond, N.A., Cronin, M.F., Freeland, H., Mantua, N., 2015. Causes and impacts of the 2014 warm anomaly in the NE Pacific. Geophys. Res. Lett. 42, 3414–3420. https://doi.org/10.1002/2015GL063306
Bopp, L., Resplandy, L., Orr, J.C., Doney, S.C., Dunne, J.P., Gehlen, M., Halloran, P., Heinze, C., Ilyina, T., Séférian, R., Tjiputra, J., Vichi, M., 2013. Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models. Biogeosciences 10, 6225–6245. https://doi.org/10.5194/bg-10-6225-2013
Brinkmann, R., 2020. Wicked problems and disasters, in: Environmental Sustainability in a Time of Change. pp. 55–82.
Brodeur, Z.P., Delaney, C., Whitin, B., Steinschneider, S., 2024. Synthetic forecast ensembles for evaluating forecast informed reservoir operations. Water Resour. Res. 60, 2023 034898. https://doi.org/10.1029/2023WR034898
Buermann, W., Forkel, M., O'Sullivan, M., Sitch, S., Friedlingstein, P., Haverd, V., Jain, A.K., Kato, E., Kautz, M., Lienert, S., Lombardozzi, D., Nabel, J.E.M.S., Tian, H., Wiltshire, A.J., Zhu, D., Smith, W.K., Richardson, A.D., 2018. Widespread seasonal compensation effects of spring warming on northern plant productivity. Nature 562, 110–114. https://doi.org/10.1038/s41586-018-0555-7
Burton, C., Rufat, S., Tate, E., 2018. Social Vulnerability: Conceptual Foundations and Geospatial Modeling, in: Vulnerability and Resilience to Natural Hazards. Cambridge University Press, pp. 51–81.
Busker, T., Moel, H., Hurk, B., Aerts, J.C., 2023. Impact-based seasonal rainfall forecasting to trigger early action for droughts. Sci. Total Environ. 898, 165506.
Castellnou, M., Guiomar, N., Rego, F., Fernandes, P.M., 2018. Fire growth patterns in the 2017 mega fire episode of October 15, central Portugal. Adv. For. Fire Res. 447–453.
Cavole, L.M., Demko, A.M., Diner, R.E., Giddings, A., Koester, I., Pagniello, C.M.L.S., Paulsen, M.-L., Ramirez-Valdez, A., Schwenck, S.M., Yen, N.K., Zill, M.E., Franks, P.J.S., 2016. Biological Impacts of the 2013–2015 Warm-Water Anomaly in the Northeast Pacific: Winners, Losers, and the Future. Oceanography issue_volume.
Ceola, S., Laio, F., Montanari, A., 2014. Satellite nighttime lights reveal increasing human exposure to floods worldwide. Geophys. Res. Lett. 41, 7184–7190.
Cheng, L., Hoerling, M., AghaKouchak, A., Livneh, B., Quan, X., Eischeid, J., 2016. How Has Human-Induced Climate Change Affected California Drought Risk? J Clim. 29, 111–120. https://doi.org/10.1175/JCLI-D-15-0260.1.
Cheung, W.W.L., Frölicher, T.L., 2020. Marine heatwaves exacerbate climate change impacts for fisheries in the northeast Pacific. Sci. Rep. 10, 6678. https://doi.org/10.1038/s41598-020-63650-z
Colten, C.E., 2006. Vulnerability and place: Flat land and uneven risk in New Orleans. Am. Anthropol. 108, 731–734.
De Sherbinin, A., Bukvic, A., Rohat, G., Gall, M., McCusker, B., Preston, B., Zhang, S., 2019. Climate vulnerability mapping: A systematic review and future prospects. Clim. Change 10, 600. https://doi.org/10.1002/wcc.600
DeFlorio, M.J., Sengupta, A., Castellano, C.M., Wang, J., Zhang, Z., Gershunov, A., Guirguis, K., Luna Niño, R., Clemesha, R.E.S., Pan, M., Xiao, M., Kawzenuk, B., Gibson, P.B., Scheftic, W.,

Broxton, P.D., Switanek, M.B., Yuan, J., Dettinger, M.D., Hecht, C.W., Cayan, D.R., Cornuelle, B.D., Miller, A.J., Kalansky, J., Delle Monache, L., Ralph, F.M., Waliser, D.E., Robertson, A.W., Zeng, X., DeWitt, D.G., Jones, J., Anderson, M.L., 2024. From California's Extreme Drought to Major Flooding: Evaluating and Synthesizing Experimental Seasonal and Subseasonal Forecasts of Landfalling Atmospheric Rivers and Extreme Precipitation during Winter 2022/23. Bull. Am. Meteorol. Soc. 105, E84–E104. https://doi.org/10.1175/BAMS-D-22-0208.1

Delaney, C.J., Hartman, R.K., Mendoza, J., Dettinger, M., Monache, L.D., Jasperse, J., Ralph, F.M., Talbot, C., Brown, J., Reynolds, D., 2020. Forecast Informed Reservoir Operations Using Ensemble Streamflow Predictions for a Multi-Purpose Reservoir in Northern California. Water Resour. Res. 56, 2019 026604,. https://doi.org/10.1029/2019WR026604

Dettinger, M.D., Ralph, F.M., Das, T., P.J.Neiman., D.R.C., 2011. Atmospheric Rivers, Floods and the Water Resources of California. Water 3, 445–478. https://doi.org/10.3390/w3020445

Di Lorenzo, E., Mantua, N., 2016. Multi-year persistence of the 2014/15 North Pacific marine heatwave. Nat. Clim. Change 6, 1042–1047. https://doi.org/10.1038/nclimate3082

Diffenbaugh, N.S., Swain, D.L., Touma, D., 2015. Anthropogenic warming has increased drought risk in California. Proc Natl Acad Sci USA 112, 3931–3936. https://doi.org/10.1073/pnas.1422385112

Ebert-Uphoff, I., Deng, Y., 2012. Causal Discovery for Climate Research Using Graphical Models. J. Clim. 25, 5648–5665. https://doi.org/10.1175/JCLI-D-11-00387.1

European Commission, Joint Research Centre, Libertà, G., Vivancos, T., Leray, T., Costa, H., San-Miguel-Ayanz, J., Branco, A., Durrant, T., Lana, F., Nuijten, D., Ahlgren, A., Löffler, P., Ferrari, D., De Rigo, D., Boca, R., Maianti, P., 2018. Forest fires in Europe, Middle East and North Africa 2017. Publications Office. https://doi.org/10.2760/663443

Faranda, D., Alberti, T., Coppola, E., Anzidei, M., 2023. Attributing Venice Acqua Alta events to a changing climate and evaluating the efficacy of MoSE adaptation strategy.

Faranda, D., Bourdin, S., Ginesta, M., Krouma, M., Noyelle, R., Pons, F., Messori, G., 2022. A climate-change attribution retrospective of some impactful weather extremes of 2021. Weather Clim. Dyn. 3, 1311–1340. https://doi.org/10.5194/wcd-3-1311-2022

Fernandes, P.M., Monteiro-Henriques, T., Guiomar, N., Loureiro, C., Barros, A.M.G., 2016. Bottom-Up Variables Govern Large-Fire Size in Portugal. Ecosystems 19, 1362–1375. https://doi.org/10.1007/s10021-016-0010-2

Ferrarin, C., Lionello, P., Orlić, M., Raicich, F., Salvadori, G., 2022. Venice as a paradigm of coastal flooding under multiple compound drivers. Sci. Rep. 12, 5754. https://doi.org/10.1038/s41598-022-09652-5

Flint, L.E., Flint, A.L., Mendoza, J., Kalansky, J., Ralph, F.M., 2018. Characterizing drought in California: new drought indices and scenario-testing in support of resource management. Ecol. Process. 7. https://doi.org/10.1186/s13717-017-0112-6.

Formetta, G., Feyen, L., 2019. Empirical evidence of declining global vulnerability to climate-related hazards. Glob. Environ. Change 57, 101920. https://doi.org/10.1016/j.gloenvcha.2019.05.004

Fouillet, A., Rey, G., Wagner, V., Laaidi, K., Empereur-Bissonnet, P., Le Tertre, A., Frayssinet, P., Bessemoulin, P., Laurent, F., De Crouy-Chanel, P., Jougla, E., Hémon, D., 2008. Has the impact of heat waves on mortality changed in France since the European heat wave of summer 2003? A study of the 2006 heat wave. Int. J. Epidemiol. 37, 309–317. https://doi.org/10.1093/ije/dym253

Frame, D.J., Rosier, S.M., Noy, I., Harrington, L.J., Carey-Smith, T., Sparrow, S.N., Stone, D.A., Dean, S.M., 2020a. Climate change attribution and the economic costs of extreme weather events: a study on damages from extreme rainfall and drought. Clim. Change 162, 781–797. https://doi.org/10.1007/s10584-020-02729-y

Frame, D.J., Wehner, M.F., Noy, I., Rosier, S.M., 2020b. The economic costs of Hurricane Harvey attributable to climate change. Clim. Change 160, 271–281. https://doi.org/10.1007/s10584-020-

02692-8
Fröhlich, C.J., 2016. Climate migrants as protestors? Dispelling misconceptions about global environmental change in pre-revolutionary Syria. Contemp. Levant 1, 38–50. https://doi.org/10.1080/20581831.2016.1149355
Frölicher, T.L., Fischer, E.M., Gruber, N., 2018. Marine heatwaves under global warming. Nature 560, 360–364. https://doi.org/10.1038/s41586-018-0383-9
Funk, C., Hoell, A., Stone, D., 2014. Examining the contribution of the observed global warming trend to the California droughts of 2012/13 and 2013/14. Bull Am Meteorol Soc 95, 11–15.
Gershunov, A., Shulgina, T., Clemesha, R.E.S., Guirguis, K., Pierce, D.W., Dettinger, M.D., Lavers, D.A., Cayan, D.R., Polade, S.D., Kalansky, J.F., Ralph, F.M., 2019. Precipitation regime change in Western North America: The role of Atmospheric Rivers. Sci. Rep. 9, 9944,. https://doi.org/10.1038/s41598-019-46169-w
Gershunov, A., Shulgina, T., Ralph, F.M., Lavers, D.A., Rutz, J.J., 2017. Assessing the climate-scale variability of atmospheric rivers affecting western North America, Geophys. Res Lett 44, 7900–7908. https://doi.org/10.1002/2017GL074175.
Gissi, E., Fraschetti, S., Micheli, F., 2019. Incorporating change in marine spatial planning: A review. Environ. Sci. Policy 92, 191–200.
Goddard, L., Gershunov, A., 2020. Impact of El Niño on Weather and Climate Extremes, in: El Niño Southern Oscillation in a Changing Climate, Geophysical Monograph Series. pp. 361–375. https://doi.org/10.1002/9781119548164.ch16
Gomes Da Costa, H., De Rigo, D., Liberta', G., Durrant, T., San-Miguel-Ayanz, J., 2020. European wildfire danger and vulnerability under a changing climate: towards integrating risk dimensions. https://doi.org/10.2760/46951 (online)
Grant, S., Tamason, C.C., Jensen, P.K.M., 2015. Climatization: A critical perspective of framing disasters as climate change events. Clim. Risk Manag. 10, 27–34. https://doi.org/10.1016/j.crm.2015.09.003
Gruber, N., Boyd, P.W., Frölicher, T.L., Vogt, M., 2021. Biogeochemical extremes and compound events in the ocean. Nature 600, 395–407. https://doi.org/10.1038/s41586-021-03981-7
Hagenlocher, M., Naumann, G., Meza, I., Blauhut, V., Cotti, D., Döll, P., Wens, M., 2023. Tackling growing drought risks—the need for a systemic perspective. Earths Future 11, 2023 003857.
Hazen, E.L., 2018. A dynamic ocean management tool to reduce bycatch and support sustainable fisheries. Sci Adv4 eaar3001. https://doi.org/10.1126/sciadv.aar3001
Hoell, A., 2022. Record low North American monsoon rainfall in 2020 reignites drought over the American Southwest.
Hore Katherine, Gaillard J. C., Davies Tim, Kearns Robin, 2020. People's Participation in Disaster-Risk Reduction: Recentering Power. Nat. Hazards Rev. 21, 04020009. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000353
Hsu, A., Sheriff, G., Chakraborty, T., 2021. Disproportionate exposure to urban heat island intensity across major US cities. Nat Commun 12, 2721. https://doi.org/10.1038/s41467-021-22799-5
Hulme, M., 2014. Attributing weather extremes to 'climate change': A review. Prog. Phys. Geogr. Earth Environ. 38, 499–511. https://doi.org/10.1177/0309133314538644
Hulme, M., O'Neill, S.J., Dessai, S., 2011. Is Weather Event Attribution Necessary for Adaptation Funding? Science 334, 764–765. https://doi.org/10.1126/science.1211740
Institute, M.P., 2023. East Africa: Drought, Food Insecurity, and Refugees.
Jasperse, J., Ralph, F.M., Anderson, M., Brekke, L., Malasavage, N., Dettinger, M.D., Forbis, J., Fuller, J., Talbot, C., Webb, R., Haynes, A., 2020. Lake Mendocino Forecast Informed Reservoir Operations Final Viability Assessment. UC San Diego.
Jézéquel, A., Dépoues, V., Guillemot, H., Trolliet, M., Vanderlinden, J.-P., Yiou, P., 2018. Behind the

veil of extreme event attribution. Clim. Change 149, 367–383. https://doi.org/10.1007/s10584-018-2252-9
Jones, M.W., Abatzoglou, J.T., Veraverbeke, S., Andela, N., Lasslop, G., Forkel, M., 2022. Global and regional trends and drivers of fire under climate change. Rev. Geophys. 60, 2020 000726. https://doi.org/10.1029/2020RG000726
Jones, T., Parrish, J.K., Peterson, W.T., Bjorkstedt, E.P., Bond, N.A., Ballance, L.T., Bowes, V., Hipfner, J.M., Burgess, H.K., Dolliver, J.E., Lindquist, K., Lindsey, J., Nevins, H.M., Robertson, R.R., Roletto, J., Wilson, L., Joyce, T., Harvey, J., 2018. Massive Mortality of a Planktivorous Seabird in Response to a Marine Heatwave. Geophys. Res. Lett. 45, 3193–3202. https://doi.org/10.1002/2017GL076164
Karamperidou, C., Stuecker, M.F., Timmermann, A., Yun, K.-S., Lee, S.-S., Jin, F.-F., Santoso, A., McPhaden, M.J., Cai, W., 2020. ENSO in a Changing Climate, in: El Niño Southern Oscillation in a Changing Climate, Geophysical Monograph Series. pp. 471–484. https://doi.org/10.1002/9781119548164.ch21
Kenya, G. of, 2023. Despatch from Cabinet, 28 February 2023.
Kimutai, J., Barnes, C., Zachariah, M., Philip, S., Kew, S., Pinto, I., Wolski, P., Koren, G., Vecchi, G., Yang, W., 2023. Human-induced climate change increased drought severity in Horn of Africa.
Kimutai, J., New, M., Wolski, P., Otto, F., 2022. Attribution of the human influence on heavy rainfall associated with flooding events during the 2012, 2016, and 2018 March-April-May seasons in Kenya. Weather Clim. Extrem. 38, 100529. https://doi.org/10.1016/j.wace.2022.100529
Kithikii, A.K., 2023. , in: THE IMPACT OF HUMANITARIAN AID IN BUILDING COMMUNITY RESILIENCE TO DROUGHT IN KITUI COUNTY. KENYA.
Köhler, L., Masson, T., Köhler, S., Kuhlicke, C., 2023. Better prepared but less resilient: the paradoxical impact of frequent flood experience on adaptive behavior and resilience. Nat. Hazards Earth Syst. Sci. 23, 2787–2806.
Kreibich, H., Baldassarre, G., Vorogushyn, S., Aerts, J.C., Apel, H., Aronica, G.T., Merz, B., 2017a. Adaptation to flood risk: Results of international paired flood event studies. Earths Future 5, 953–965.
Kreibich, H., Baldassarre, G., Vorogushyn, S., Aerts, J.C., Apel, H., Aronica, G.T., Merz, B., 2017b. Adaptation to flood risk: Results of international paired flood event studies. Earths Future 5, 953–965.
Kreibich, H., Van Loon, A.F., Schröter, K., Ward, P.J., Mazzoleni, M., Sairam, N., Abeshu, G.W., Agafonova, S., AghaKouchak, A., Aksoy, H., Alvarez-Garreton, C., Aznar, B., Balkhi, L., Barendrecht, M.H., Biancamaria, S., Bos-Burgering, L., Bradley, C., Budiyono, Y., Buytaert, W., Capewell, L., Carlson, H., Cavus, Y., Couasnon, A., Coxon, G., Daliakopoulos, I., de Ruiter, M.C., Delus, C., Erfurt, M., Esposito, G., François, D., Frappart, F., Freer, J., Frolova, N., Gain, A.K., Grillakis, M., Grima, J.O., Guzmán, D.A., Huning, L.S., Ionita, M., Kharlamov, M., Khoi, D.N., Kieboom, N., Kireeva, M., Koutroulis, A., Lavado-Casimiro, W., Li, H.-Y., LLasat, M.C., Macdonald, D., Mård, J., Mathew-Richards, H., McKenzie, A., Mejia, A., Mendiondo, E.M., Mens, M., Mobini, S., Mohor, G.S., Nagavciuc, V., Ngo-Duc, T., Thao Nguyen Huynh, T., Nhi, P.T.T., Petrucci, O., Nguyen, H.Q., Quintana-Seguí, P., Razavi, S., Ridolfi, E., Riegel, J., Sadik, M.S., Savelli, E., Sazonov, A., Sharma, S., Sörensen, J., Arguello Souza, F.A., Stahl, K., Steinhausen, M., Stoelzle, M., Szalińska, W., Tang, Q., Tian, F., Tokarczyk, T., Tovar, C., Tran, T.V.T., Van Huijgevoort, M.H.J., van Vliet, M.T.H., Vorogushyn, S., Wagener, T., Wang, Y., Wendt, D.E., Wickham, E., Yang, L., Zambrano-Bigiarini, M., Blöschl, G., Di Baldassarre, G., 2022. The challenge of unprecedented floods and droughts in risk management. Nature 608, 80–86. https://doi.org/10.1038/s41586-022-04917-5
Kuhlicke, C., Brito, M.M., Bartkowski, B., Botzen, W., Doğulu, C., Han, S., Rufat, S., 2023. Spinning in circles? A systematic review on the role of theory in social vulnerability, resilience and adaptation research. Glob. Environ. Change 80, 102672.

Kuo, Y.-N., Kim, H., Lehner, F., 2023. Anthropogenic Aerosols Contribute to the Recent Decline in Precipitation Over the U.S. Southwest. Geophys. Res. Lett. 50, e2023GL105389. https://doi.org/10.1029/2023GL105389
Lahsen, M., Couto, G. de A., Lorenzoni, I., 2020. When climate change is not blamed: the politics of disaster attribution in international perspective. Clim. Change 158, 213–233. https://doi.org/10.1007/s10584-019-02642-z
Lahsen, M., Ribot, J., 2022. Politics of attributing extreme events and disasters to climate change. WIREs Clim. Change 13, e750. https://doi.org/10.1002/wcc.750
Lam, M.R., Matanó, A., Loon, A.F., Odongo, R.A., Teklesadik, A.D., Wamucii, C.N., Teuling, A.J., 2023. Linking reported drought impacts with drought indices, water scarcity and aridity: the case of Kenya. Nat. Hazards Earth Syst. Sci. 23, 2915–2936.
Laufkötter, C., Zscheischler, J., Frölicher, T.L., 2020. High-impact marine heatwaves attributable to human-induced global warming. Science 369, 1621–1625. https://doi.org/10.1126/science.aba0690
Le Grix, N., Zscheischler, J., Laufkötter, C., Rousseaux, C.S., Frölicher, T.L., 2021. Compound high-temperature and low-chlorophyll extremes in the ocean over the satellite period. Biogeosciences 18, 2119–2137. https://doi.org/10.5194/bg-18-2119-2021
Lehner, F., Deser, C., Simpson, I.R., Terray, L., 2018. Attributing the U.S. Southwest's Recent Shift Into Drier Conditions. Geophys. Res. Lett. 45, 6251–6261. https://doi.org/10.1029/2018GL078312
Leising, A.W.; S., 2016. State of the California Current 2014-15: Impacts of the Warm-Water "Blob."
Lewis, J., Kelman, I., 2012. The Good, The Bad and The Ugly: Disaster Risk Reduction (DRR) Versus Disaster Risk Creation (DRC). PLoS Curr. 4, e4f8d4eaec6af8. https://doi.org/10.1371/4f8d4eaec6af8
Li, D., Chen, Y., Qi, J., Zhu, Y., Lu, C., Yin, B., 2023. Attribution of the July 2021 Record-Breaking Northwest Pacific Marine Heatwave to Global Warming, Atmospheric Circulation, and ENSO. Bull Amer Meteor Soc 104, 291-297,. https://doi.org/10.1175/BAMS-D-22-0142.1.
Lionello, P., Barriopedro, D., Ferrarin, C., Nicholls, R.J., Orlić, M., Raicich, F., Reale, M., Umgiesser, G., Vousdoukas, M., Zanchettin, D., 2021. Extreme floods of Venice: characteristics, dynamics, past and future evolution (review article). Nat Hazards Earth Syst Sci 21, 2705–2731. https://doi.org/10.5194/nhess-21-2705-2021
Litzow, M.A., Malick, M.J., Abookire, A.A., Duffy-Anderson, J., Laurel, B.J., Ressler, P.H., Rogers, L.A., 2021. Using a climate attribution statistic to inform judgments about changing fisheries sustainability. Sci. Rep. 11, 23924. https://doi.org/10.1038/s41598-021-03405-6
Litzow, M.A., Mueter, F.J., Hobday, A.J., 2014. Reassessing regime shifts in the North Pacific: incremental climate change and commercial fishing are necessary for explaining decadal-scale biological variability. Glob. Change Biol. 20, 38–50. https://doi.org/10.1111/gcb.12373
Lloyd, E.A., Shepherd, T.G., 2023. Foundations of attribution in climate-change science. Env Res Clim 2, 035014.
Lloyd, E.A., Shepherd, T.G., 2020. Environmental catastrophes, climate change, and attribution. Ann NY Acad Sci 1469, 105–124.
López, J., Way, D.A., Sadok, W., 2021. Systemic effects of rising atmospheric vapor pressure deficit on plant physiology and productivity. Glob. Change Biol. 27, 1704–1720. https://doi.org/10.1111/gcb.15548
Lund, J., Medellin-Azuara, J., Durand, J., Stone, K., 2018. Lessons from California's 2012-2016 Drought. J Water Res Plan Man 144, 04018067. https://doi.org/10.1061/(Asce)Wr.1943-5452.0000984
Maldonado, G., Greenland, S., 2002. Estimating causal effects. Int. J. Epidemiol. 31, 422-429,. https://doi.org/10.1093/ije/31.2.422
Mankin, J., Simpson, I., Hoell, A., Fu, R., Lisonbee, J., Sheffield, A., Barrie, D., 2021. NOAA

drought task force report on the 2020–2021 southwestern US drought.
Matanó, A., Ruiter, M.C., Koehler, J., Ward, P.J., Loon, A.F., 2022. Caught between extremes: Understanding human-water interactions during drought-to-flood events in the Horn of Africa. Earths Future 10, 2022 002747.
McNally, A., Verdin, K., Harrison, L., Getirana, A., Jacob, J., Shukla, S., Arsenault, K., Peters-Lidard, C., Verdin, J.P., 2019. Acute Water-Scarcity Monitoring for Africa. Water 11. https://doi.org/10.3390/w11101968
Medellín-Azuara, J., 2022. Economic Impacts of the 2020-2022 Drought on California Agriculture.
Mengel, M., Treu, S., Lange, S., Frieler, K., 2021. ATTRICI v1.1 – counterfactual climate for impact attribution, Geosci. Model Dev 14, 5269-5284,. https://doi.org/10.5194/gmd-14-5269-2021
Meredith, E.P., Semenov, V.A., Maraun, D., Park, W., Chernokulsky, A.V., 2015. Crucial role of Black Sea warming in amplifying the 2012 Krymsk precipitation extreme. Nat. Geosci. 8, 615–619. https://doi.org/10.1038/ngeo2483
Meza, I., Siebert, S., Döll, P., Kusche, J., Herbert, C., Eyshi Rezaei, E., Hagenlocher, M., 2020. Global-scale drought risk assessment for agricultural systems. Nat. Hazards Earth Syst. Sci. 20, 695–712.
Mitchell, D., Heaviside, C., Vardoulakis, S., Huntingford, C., Masato, G., P Guillod, B., Frumhoff, P., Bowery, A., Wallom, D., Allen, M., 2016. Attributing human mortality during extreme heat waves to anthropogenic climate change. Environ. Res. Lett. 11, 074006. https://doi.org/10.1088/1748-9326/11/7/074006
Mogen, S.C., Lovenduski, N.S., Dallmann, A.R., Gregor, L., Sutton, A.J., Bograd, S.J., Quiros, N.C., Di Lorenzo, E., Hazen, E.L., Jacox, M.G., Buil, M.P., Yeager, S., 2022. Ocean Biogeochemical Signatures of the North Pacific Blob. Geophys. Res. Lett. 49, e2021GL096938. https://doi.org/10.1029/2021GL096938
Murakami, H., 2018. Dominant effect of relative tropical Atlantic warming on major hurricane occurrence. Science 362, 794–799. https://doi.org/10.1126/science.aat6711
NET), F.E.W.S.N. (FEWS, 2017. Kenya Food Security Outlook: February to September 2017. USAID.
NET), F.E.W.S.N. (FEWS, 2013. Kenya Food Security In Brief: 2013. USAID.
Newman, R., Noy, I., 2023. The global costs of extreme weather that are attributable to climate change. Nat. Commun. 14, 6103. https://doi.org/10.1038/s41467-023-41888-1
News, U.N., 2022. UN chief condemns recent deadly armed group attacks in eastern DR Congo.
Ng, A., Yap, N.T., 2011. Drought Preparedness and Response as if Development Matters: Case Studies from Kenya. J. Rural Community Dev. 6.
Nyberg, Y., Jonsson, M., Ambjörnsson, E.L., Wetterlind, J., Öborn, I., 2020. Smallholders' awareness of adaptation and coping measures to deal with rainfall variability in Western Kenya. Agroecol. Sustain. Food Syst. 44, 1280-1308,. https://doi.org/10.1080/21683565.2020.1782305
O'keefe, P., Westgate, K., Wisner, B., 1976. Taking the naturalness out of natural disasters. Nature 260, 566–567.
Oliveira, M., Delerue-Matos, C., Pereira, M.C., Morais, S., 2020. Environmental Particulate Matter Levels during 2017 Large Forest Fires and Megafires in the Center Region of Portugal: A Public Health Concern? Int. J. Environ. Res. Public. Health 17. https://doi.org/10.3390/ijerph17031032
Oliver, E.C.J., Donat, M.G., Burrows, M.T., 2018. Longer and more frequent marine heatwaves over the past century. Nat Commun 9, 1324. https://doi.org/10.1038/s41467-018-03732-9
Olsson, L., Thorén, H., Harnesk, D., Persson, J., 2022. Ethics of probabilistic extreme event attribution in climate change science: A critique. Earths Future 10, 2021 002258. https://doi.org/10.1029/2021EF002258
Otto, F.E.L., 2017. Attribution of Weather and Climate Events. Annu. Rev. Environ. Resour. 42, 627–

646. https://doi.org/10.1146/annurev-environ-102016-060847
Otto, F.E.L., Minnerop, P., Raju, E., Harrington, L.J., Stuart-Smith, R.F., Boyd, E., James, R., Jones, R., Lauta, K.C., 2022. Causality and the fate of climate litigation: The role of the social superstructure narrative. Glob. Policy 13, 736–750. https://doi.org/10.1111/1758-5899.13113
Paciorek, C.J., Wehner, M.F., 2024. Comment on "Five Decades of Observed Daily Precipitation Reveal Longer and More Variable Drought Events Across Much of the Western United States." Geophys. Res. Lett. 51, e2023GL104550. https://doi.org/10.1029/2023GL104550
Pall, P., Aina, T., Stone, D.A., Stott, P.A., Nozawa, T., Hilberts, A.G.J., Lohmann, D., Allen, M.R., 2011. Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000. Nature 470, 382–385. https://doi.org/10.1038/nature09762
Perkins, O., Kasoar, M., Voulgarakis, A., Smith, C., Mistry, J., Millington, J.D.A., 2024. A global behavioural model of human fire use and management: WHAM! v1.0. Geosci. Model Dev. 17, 3993–4016. https://doi.org/10.5194/gmd-17-3993-2024
Philip, S., Kew, S., van Oldenborgh, G.J., Otto, F., Vautard, R., van der Wiel, K., King, A., Lott, F., Arrighi, J., Singh, R., van Aalst, M., 2020. A protocol for probabilistic extreme event attribution analyses. Adv Stat Clim Meteorol Ocean. 6, 177–203. https://doi.org/10.5194/ascmo-6-177-2020
Piatt, J.F., Parrish, J.K., Renner, H.M., Schoen, S.K., Jones, T.T., Arimitsu, M.L., Kuletz, K.J., Bodenstein, B., García-Reyes, M., Duerr, R.S., Corcoran, R.M., Kaler, R.S.A., McChesney, G.J., Golightly, R.T., Coletti, H.A., Suryan, R.M., Burgess, H.K., Lindsey, J., Lindquist, K., Warzybok, P.M., Jahncke, J., Roletto, J., Sydeman, W.J., 2020. Extreme mortality and reproductive failure of common murres resulting from the northeast Pacific marine heatwave of 2014-2016. PLOS ONE 15, e0226087. https://doi.org/10.1371/journal.pone.0226087
Program, W.F., 2022. Horn of Africa: Extreme Drought Deepens Hunger in Region Facing Conflict.
Qian, C., Ye, Y., Bevacqua, E., Zscheischler, J., 2023. Human influences on spatially compounding flooding and heatwave events in China and future increasing risks. Weather Clim. Extrem. 42, 100616. https://doi.org/10.1016/j.wace.2023.100616
Quandt, A., 2021. Coping with drought: Narratives from smallholder farmers in semi-arid Kenya. Int. J. Disaster Risk Reduct. 57, 102168. https://doi.org/10.1016/j.ijdrr.2021.102168
Raju, E., Boyd, E., Otto, F., 2022. Stop blaming the climate for disasters. Commun. Earth Environ. 3, 1.
Ralph, F.M., Cannon, F., Tallapragada, V., Davis, C.A., Doyle, J.D., Pappenberger, F., Subramanian, A., Wilson, A.M., Lavers, D.A., Reynolds, C.A., Haase, J.S., Centurioni, L., Ingleby, B., Rutz, J.J., Cordeira, J.M., Zheng, M., Hecht, C., Kawzenuk, B., Monache, L.D., 2020. West Coast Forecast Challenges and Development of Atmospheric River Reconnaissance. Bull Amer Meteor Soc 101, 1357-1377,. https://doi.org/10.1175/BAMS-D-19-0183.1
Ramos, A.M., Russo, A., DaCamara, C.C., Nunes, S., Sousa, P., Soares, P., Lima, M.M., Hurduc, A., Trigo, R.M., 2023. The compound event that triggered the destructive fires of October 2017 in Portugal. IScience 26.
Ribot, J., Faye, P., Turner, M.D., 2020. Climate of Anxiety in the Sahel: Emigration in Xenophobic Times. Public Cult. 32, 45–75. https://doi.org/10.1215/08992363-7816293
Risser, M.D., Wehner, M.F., 2017. Attributable human-induced changes in the likelihood and magnitude of the observed extreme precipitation during Hurricane Harvey. Geophys. Res. Lett. 44, 12,457-12,464. https://doi.org/10.1002/2017GL075888
Robin, Y., Ribes, A., 2020. Nonstationary extreme value analysis for event attribution combining climate models and observations. Adv. Stat. Climatol. Meteorol. Oceanogr. 6, 205–221. https://doi.org/10.5194/ascmo-6-205-2020
Rodrigues, A., Santiago, A., Laím, L., Viegas, D.X., Zêzere, J.L., 2022. Rural Fires—Causes of Human Losses in the 2017 Fires in Portugal. Appl. Sci. 12. https://doi.org/10.3390/app122412561

Rufat, S., Fekete, A., Armaş, I., Hartmann, T., Kuhlicke, C., Prior, T., Wisner, B., 2020. Swimming alone? Why linking flood risk perception and behavior requires more than "it's the individual, stupid." Water 7, 1462.
Rufat, S., Tate, E., Burton, C.G., Maroof, A.S., 2015. Social vulnerability to floods: Review of case studies and implications for measurement. Int. J. Disaster Risk Reduct. 14, 470–486.
Rufat, S., Tate, E., Emrich, C.T., Antolini, F., 2019. How Valid Are Social Vulnerability Models? Ann. Am. Assoc. Geogr. 109, 1131–1153. https://doi.org/10.1080/24694452.2018.1535887
Ruiter, M.C., Van Loon, A.F., 2022. The challenges of dynamic vulnerability and how to assess it. IScience 25.
Rusca, M., Savelli, E., Baldassarre, G., Biza, A., Messori, G., 2023. Unprecedented droughts are expected to exacerbate urban inequalities in Southern Africa. Nat. Clim. Change 13, 98–105.
Sanders, B.F., Schubert, J.E., Kahl, D.T., Mach, K.J., Brady, D., AghaKouchak, A., Forman, F., Matthew, R.A., Ulibarri, N., Davis, S.J., 2023. Large and inequitable flood risks in Los Angeles, California. Nat. Sustain. 6, 47–57. https://doi.org/10.1038/s41893-022-00977-7
Santora, J.A., Mantua, N.J., Schroeder, I.D., Field, J.C., Hazen, E.L., Bograd, S.J., Sydeman, W.J., Wells, B.K., Calambokidis, J., Saez, L., Lawson, D., Forney, K.A., 2020. Habitat compression and ecosystem shifts as potential links between marine heatwave and record whale entanglements. Nat. Commun. 11, 536. https://doi.org/10.1038/s41467-019-14215-w
Savelli, E., Rusca, M., Cloke, H., Di Baldassarre, G., 2021. Don't blame the rain: Social power and the 2015–2017 drought in Cape Town. J. Hydrol. 594, 125953. https://doi.org/10.1016/j.jhydrol.2020.125953
Schaller, N., Kay, A.L., Lamb, R., Massey, N.R., van Oldenborgh, G.J., Otto, F.E.L., Sparrow, S.N., Vautard, R., Yiou, P., Ashpole, I., Bowery, A., Crooks, S.M., Haustein, K., Huntingford, C., Ingram, W.J., Jones, R.G., Legg, T., Miller, J., Skeggs, J., Wallom, D., Weisheimer, A., Wilson, S., Stott, P.A., Allen, M.R., 2016. Human influence on climate in the 2014 southern England winter floods and their impacts. Nat. Clim. Change 6, 627–634. https://doi.org/10.1038/nclimate2927
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. Clim. 28, 6997–7024. https://doi.org/10.1175/JCLI-D-14-00860.1
Seager, R., Ting, M., Alexander, P., Nakamura, J., Liu, H., Li, C., Simpson, I.R., 2022. Mechanisms of a Meteorological Drought Onset: Summer 2020 to Spring 2021 in Southwestern North America. J. Clim. 35, 7367–7385. https://doi.org/10.1175/JCLI-D-22-0314.1
Sebastian, A., Gori, A., Blessing, R.B., van der Wiel, K., Bass, B., 2019. Disentangling the impacts of human and environmental change on catchment response during Hurricane Harvey. Environ. Res. Lett. 14, 124023. https://doi.org/10.1088/1748-9326/ab5234
Selby, J., Dahi, O.S., Fröhlich, C., Hulme, M., 2017. Climate change and the Syrian civil war revisited. Polit. Geogr. 60, 232–244. https://doi.org/10.1016/j.polgeo.2017.05.007
Seneviratne, S., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Di Luca, A., Ghosh, S., Iskandar, I., Kossin, J., Lewis, S., 2021. Weather and climate extreme events in a changing climate Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Camb. UK N. Y. USA.
Shepherd, T.G., 2016. A common framework for approaches to extreme event attribution. Curr Clim Change Rep 2, 28-38,. https://doi.org/10.1007/s40641-016-0033-y.
Shukla, S., Safeeq, M., AghaKouchak, A., Guan, K., Funk, C., 2015. Temperature impacts on the water year 2014 drought in California. Geophys. Res. Lett. 42, 4384–4393. https://doi.org/10.1002/2015GL063666
Simpson, N.P., Mach, K.J., Constable, A., Hess, J., Hogarth, R., Howden, M., Lawrence, J., Lempert, R.J., Muccione, V., Mackey, B., others, 2021. A framework for complex climate change risk

assessment. One Earth 4, 489–501.
Sippel, S., Forkel, M., Rammig, A., Thonicke, K., Flach, M., Heimann, M., Otto, F.E.L., Reichstein, M., Mahecha, M.D., 2017. Contrasting and interacting changes in simulated spring and summer carbon cycle extremes in European ecosystems. Environ. Res. Lett. 12, 075006. https://doi.org/10.1088/1748-9326/aa7398
Smiley, K.T., Noy, I., Wehner, M.F., Frame, D., Sampson, C.C., Wing, O.E.J., 2022. Social inequalities in climate change-attributed impacts of Hurricane Harvey. Nat. Commun. 13, 3418. https://doi.org/10.1038/s41467-022-31056-2
Sudmeier-Rieux, K., Arce-Mojica, T., Boehmer, H.J., Doswald, N., Emerton, L., Friess, D.A., Galvin, S., Hagenlocher, M., James, H., Laban, P., Lacambra, C., Lange, W., McAdoo, B.G., Moos, C., Mysiak, J., Narvaez, L., Nehren, U., Peduzzi, P., Renaud, F.G., Sandholz, S., Schreyers, L., Sebesvari, Z., Tom, T., Triyanti, A., van Eijk, P., van Staveren, M., Vicarelli, M., Walz, Y., 2021. Scientific evidence for ecosystem-based disaster risk reduction. Nat. Sustain. 4, 803–810. https://doi.org/10.1038/s41893-021-00732-4
Sumargo, E., McMillan, H., Weihs, R., Ellis, C.J., Wilson, A.M., Ralph, F.M., 2021. A soil moisture monitoring network to assess controls on runoff generation during atmospheric river events. Hydrol. Process. 35, e13998. https://doi.org/10.1002/hyp.13998
Swain, D.L., Langenbrunner, B., Neelin, J.D., Hall, A., 2018. Increasing precipitation volatility in twenty-first-century California. Nat. Clim. Change 8, 427–433. https://doi.org/10.1038/s41558-018-0140-y
Swain, D.L., Tsiang, M., Haugen, M., Singh, D., Charland, A., Rajaratnam, B., Diffenbaugh, N.S., 2014. The extraordinary California drought of 2013/2014: Character, context, and the role of climate change. Bull Am Meteorol Soc 95:S3–S7.
System (EFFIS), E.F.F.I., 2024. EFFIS Statistics Portal.
Tait, L.W., 2021. Loss of giant kelp, Macrocystis pyrifera, driven by marine heatwaves and exacerbated by poor water clarity in New Zealand. Front. Mar. Sci. 8, 721087.
Tebaldi, C., Ranasinghe, R., Vousdoukas, M., Rasmussen, D.J., Vega-Westhoff, B., Kirezci, E., Kopp, R.E., Sriver, R., Mentaschi, L., 2021. Extreme sea levels at different global warming levels. Nat. Clim. Change 11, 746–751. https://doi.org/10.1038/s41558-021-01127-1
Tradowsky, J.S., Philip, S.Y., Kreienkamp, F., Kew, S.F., Lorenz, P., Arrighi, J., Bettmann, T., Caluwaerts, S., Chan, S.C., De Cruz, L., de Vries, H., Demuth, N., Ferrone, A., Fischer, E.M., Fowler, H.J., Goergen, K., Heinrich, D., Henrichs, Y., Kaspar, F., Lenderink, G., Nilson, E., Otto, F.E.L., Ragone, F., Seneviratne, S.I., Singh, R.K., Skålevåg, A., Termonia, P., Thalheimer, L., van Aalst, M., Van den Bergh, J., Van de Vyver, H., Vannitsem, S., van Oldenborgh, G.J., Van Schaeybroeck, B., Vautard, R., Vonk, D., Wanders, N., 2023. Attribution of the heavy rainfall events leading to severe flooding in Western Europe during July 2021. Clim. Change 176, 90. https://doi.org/10.1007/s10584-023-03502-7
Trenberth, K.E., Fasullo, J.T., Shepherd, T.G., 2015. Attribution of climate extreme events. Nat. Clim. Change 5, 725–730. https://doi.org/10.1038/nclimate2657
Tseng, Y.-H., Ding, R., Huang, X., 2017. The warm Blob in the northeast Pacific—the bridge leading to the 2015/16 El Niño. Environ. Res. Lett. 12, 054019. https://doi.org/10.1088/1748-9326/aa67c3
Turco, M., Jerez, S., Augusto, S., 2019. Climate drivers of the 2017 devastating fires in Portugal. Sci Rep 9, 13886. https://doi.org/10.1038/s41598-019-50281-2
Uhe, P., Philip, S., Kew, S., Shah, K., Kimutai, J., Mwangi, E., van Oldenborgh, G.J., Singh, R., Arrighi, J., Jjemba, E., Cullen, H., Otto, F., 2018. Attributing drivers of the 2016 Kenyan drought. Int. J. Climatol. 38, e554–e568. https://doi.org/10.1002/joc.5389
Umgiesser, G., Bajo, M., Ferrarin, C., Cucco, A., Lionello, P., Zanchettin, D., Papa, A., Tosoni, A., Ferla, M., Coraci, E., Morucci, S., Crosato, F., Bonometto, A., Valentini, A., Orlić, M., Haigh, I.D.,

Nielsen, J.W., Bertin, X., Fortunato, A.B., Pérez Gómez, B., Alvarez Fanjul, E., Paradis, D., Jourdan, D., Pasquet, A., Mourre, B., Tintoré, J., Nicholls, R.J., 2021. The prediction of floods in Venice: methods, models and uncertainty (review article). Nat Hazards Earth Syst Sci 21, 2679–2704. https://doi.org/10.5194/nhess-21-2679-2021

U.S. Drought Monitor, n.d. Drought Classification.

Van Loon, A.F., Rangecroft, S., Coxon, G., Werner, M., Wanders, N., Di Baldassarre, G., Tijdeman, E., Bosman, M., Gleeson, T., Nauditt, A., Aghakouchak, A., Breña-Naranjo, J.A., Cenobio-Cruz, O., Costa, A.C., Fendekova, M., Jewitt, G., Kingston, D.G., Loft, J., Mager, S.M., Mallakpour, I., Masih, I., Maureira-Cortés, H., Toth, E., Van Oel, P., Van Ogtrop, F., Verbist, K., Vidal, J.-P., Wen, L., Yu, M., Yuan, X., Zhang, M., Van Lanen, H.A.J., 2022. Streamflow droughts aggravated by human activities despite management. Environ. Res. Lett. 17, 044059. https://doi.org/10.1088/1748-9326/ac5def

Van Loon, A.F., Stahl, K., Di Baldassarre, G., Clark, J., Rangecroft, S., Wanders, N., Gleeson, T., Van Dijk, A.I.J.M., Tallaksen, L.M., Hannaford, J., Uijlenhoet, R., Teuling, A.J., Hannah, D.M., Sheffield, J., Svoboda, M., Verbeiren, B., Wagener, T., Van Lanen, H.A.J., 2016. Drought in a human-modified world: reframing drought definitions, understanding, and analysis approaches. Hydrol Earth Syst Sci 20, 3631–3650. https://doi.org/10.5194/hess-20-3631-2016

van Oldenborgh, G.J., Krikken, F., Lewis, S., Leach, N.J., Lehner, F., Saunders, K.R., van Weele, M., Haustein, K., Li, S., Wallom, D., Sparrow, S., Arrighi, J., Singh, R.K., van Aalst, M.K., Philip, S.Y., Vautard, R., Otto, F.E.L., 2021. Attribution of the Australian bushfire risk to anthropogenic climate change. Nat. Hazards Earth Syst. Sci. 21, 941–960. https://doi.org/10.5194/nhess-21-941-2021

Vicedo-Cabrera, A.M., Schrijver, E., Schumacher, D.L., Ragettli, M.S., Fischer, E.M., Seneviratne, S.I., 2023. The footprint of human-induced climate change on heat-related deaths in the summer of 2022 in Switzerland. Environ. Res. Lett. 18, 074037. https://doi.org/10.1088/1748-9326/ace0d0

Vicedo-Cabrera, A.M., Scovronick, N., Sera, F., Royé, D., Schneider, R., Tobias, A., Astrom, C., Guo, Y., Honda, Y., Hondula, D.M., Abrutzky, R., Tong, S., Coelho, M. de S.Z.S., Saldiva, P.H.N., Lavigne, E., Correa, P.M., Ortega, N.V., Kan, H., Osorio, S., Kyselý, J., Urban, A., Orru, H., Indermitte, E., Jaakkola, J.J.K., Ryti, N., Pascal, M., Schneider, A., Katsouyanni, K., Samoli, E., Mayvaneh, F., Entezari, A., Goodman, P., Zeka, A., Michelozzi, P., de'Donato, F., Hashizume, M., Alahmad, B., Diaz, M.H., Valencia, C.D.L.C., Overcenco, A., Houthuijs, D., Ameling, C., Rao, S., Di Ruscio, F., Carrasco-Escobar, G., Seposo, X., Silva, S., Madureira, J., Holobaca, I.H., Fratianni, S., Acquaotta, F., Kim, H., Lee, W., Iniguez, C., Forsberg, B., Ragettli, M.S., Guo, Y.L.L., Chen, B.Y., Li, S., Armstrong, B., Aleman, A., Zanobetti, A., Schwartz, J., Dang, T.N., Dung, D.V., Gillett, N., Haines, A., Mengel, M., Huber, V., Gasparrini, A., 2021. The burden of heat-related mortality attributable to recent human-induced climate change. Nat. Clim. Change 11, 492–500. https://doi.org/10.1038/s41558-021-01058-x

Vicente-Serrano, S.M., Lopez-Moreno, J.I., Beguería, S., Lorenzo-Lacruz, J., Sanchez-Lorenzo, A., García-Ruiz, J.M., Espejo, F., 2014. Evidence of increasing drought severity caused by temperature rise in southern Europe. Environ. Res. Lett. 9, 044001. https://doi.org/10.1088/1748-9326/9/4/044001

Vicente-Serrano, S.M., Peña-Gallardo, M., Hannaford, J., Murphy, C., Lorenzo-Lacruz, J., Dominguez-Castro, F., López-Moreno, J.I., Beguería, S., Noguera, I., Harrigan, S., Vidal, J.-P., 2019. Climate, Irrigation, and Land Cover Change Explain Streamflow Trends in Countries Bordering the Northeast Atlantic. Geophys. Res. Lett. 46, 10821–10833. https://doi.org/10.1029/2019GL084084

Viegas, D.X., Almeida, M.F., Ribeiro, L.M., Raposo, J., Viegas, M.T., Oliveira, R., Alves, D., Pinto, C., Rodrigues, A., Ribeiro, C., 2019. Análise dos Incêndios Florestais Ocorridos a 15 de outubro de 2017. Cent. Estud. Sobre Incêndios Florestais CEIFADAILAETA.

Walker, A.P., De Kauwe, M.G., Bastos, A., Belmecheri, S., Georgiou, K., Keeling, R.F., McMahon, S.M., Medlyn, B.E., Moore, D.J.P., Norby, R.J., Zaehle, S., Anderson-Teixeira, K.J., Battipaglia, G.,

Brienen, R.J.W., Cabugao, K.G., Cailleret, M., Campbell, E., Canadell, J.G., Ciais, P., Craig, M.E., Ellsworth, D.S., Farquhar, G.D., Fatichi, S., Fisher, J.B., Frank, D.C., Graven, H., Gu, L., Haverd, V., Heilman, K., Heimann, M., Hungate, B.A., Iversen, C.M., Joos, F., Jiang, M., Keenan, T.F., Knauer, J., Körner, C., Leshyk, V.O., Leuzinger, S., Liu, Y., MacBean, N., Malhi, Y., McVicar, T.R., Penuelas, J., Pongratz, J., Powell, A.S., Riutta, T., Sabot, M.E.B., Schleucher, J., Sitch, S., Smith, W.K., Sulman, B., Taylor, B., Terrer, C., Torn, M.S., Treseder, K.K., Trugman, A.T., Trumbore, S.E., van Mantgem, P.J., Voelker, S.L., Whelan, M.E., Zuidema, P.A., 2021. Integrating the evidence for a terrestrial carbon sink caused by increasing atmospheric CO2. New Phytol. 229, 2413–2445. https://doi.org/10.1111/nph.16866

Wang, S.-Y.S., Yoon, J., Gillies, R.R., Hsu, H.-H., 2017. The California Drought, in: Wang, S.-.-Y.S., Yoon, J.-H., Funk, C.C., Gillies), R.R. (Eds.), Climate Extremes. https://doi.org/10.1002/9781119068020.ch13

Ward, P.J., Jongman, B., Weiland, F.S., Bouwman, A., Beek, R., Bierkens, M.F., Winsemius, H.C., 2013. Assessing flood risk at the global scale: model setup, results, and sensitivity. Environ. Res. Lett. 8, 044019.

Wehner, M., Sampson, C., 2021. Attributable human-induced changes in the magnitude of flooding in the Houston, Texas region during Hurricane Harvey. Clim. Change 166, 20. https://doi.org/10.1007/s10584-021-03114-z

Wendt, D.E., Loon, A.F., Bloomfield, J.P., Hannah, D.M., 2020. Asymmetric impact of groundwater use on groundwater droughts. Hydrol. Earth Syst. Sci. 24, 4853–4868.

Wens, M.L., Loon, A.F., Veldkamp, T.I., Aerts, J.C., 2022. Education, financial aid, and awareness can reduce smallholder farmers' vulnerability to drought under climate change. Nat. Hazards Earth Syst. Sci. 22, 1201–1232.

Wens, M.L., Loon, A.F., Veldkamp, T.I., Aerts, J.C., 2021. Education, financial aid and awareness can reduce smallholder farmers' vulnerability to drought under climate change. Nat. Hazards Earth Syst. Sci. Discuss. 1–36.

Whitney, F.A., 2015. Anomalous winter winds decrease 2014 transition zone productivity in the NE Pacific. Geophys. Res. Lett. 42, 428–431. https://doi.org/10.1002/2014GL062634

Williams, A.P., 2020. Large contribution from anthropogenic warming to an emerging North American megadrought. Science 368, 314–318. https://doi.org/10.1126/science.aaz9600

Williams, A.P., Seager, R., Abatzoglou, J.T., Cook, B.I., Smerdon, J.E., Cook, E.R., 2015. Contribution of anthropogenic warming to California drought during 2012–2014. Geophys. Res. Lett. 42, 6819–6828. https://doi.org/10.1002/2015GL064924

Wilson, A.M., Ralph, F.M., Talbot, C., James, J., Leahigh, J., Hutchinson, A., Woodside, G.D., Anderson, M., Alden, D., Cooper, A., Delaney, C., Downer, C., Hartman, R., Haynes, A., Hecht, C., Kawzenuk, B., McGurk, G., Reynolds, D., Sumargo, E., Turnbull, S.J., Weihs, R.R., Whitin, B., Jasperse, L., Yao, P., Downing, B., 2022. Advances Toward FIRO Objectives Supported by Observations - Progress and Future Directions. Presented at the AGU Fall Meeting Abstracts, pp. H35L-1275.

Wisner, B., 2016. Vulnerability as concept, model, metric, and tool, in: Oxford Research Encyclopedia of Natural Hazard Science.

World Food Programme (WFP), 2023. WFP Kenya Country Brief, February 2023.

Wyatt, A.M., Resplandy, L., Marchetti, A., 2022. Ecosystem impacts of marine heat waves in the northeast Pacific. Biogeosciences 19, 5689–5705. https://doi.org/10.5194/bg-19-5689-2022

Zanchettin, D., Bruni, S., Raicich, F., Lionello, P., Adloff, F., Androsov, A., Antonioli, F., Artale, V., Carminati, E., Ferrarin, C., Fofonova, V., Nicholls, R.J., Rubinetti, S., Rubino, A., Sannino, G., Spada, G., Thieblemont, R., Tsimplis, M., Umgiesser, G., Vignudelli, S., Woppelmann, G., Zerbini, S., 2021. Sea-level rise in Venice: historic and future trends (review article. Nat. Hazards Earth Syst.

Sci. 21, 2643–2678. https://doi.org/10.5194/nhess-21-2643-2021
Zhang, R., 2019. A review of the role of the Atlantic meridional overturning circulation in Atlantic multidecadal variability and associated climate impacts. Rev. Geophys. 57, 316–375.
Zhang, W., Villarini, G., Vecchi, G.A., Smith, J.A., 2018. Urbanization exacerbated the rainfall and flooding caused by hurricane Harvey in Houston. Nature 563, 384–388. https://doi.org/10.1038/s41586-018-0676-z
Zscheischler, J., 2020. A typology of compound weather and climate events. Nat. Rev. Earth Environ. 1, 333–347.
Zscheischler, J., Lehner, F., 2022. Attributing Compound Events to Anthropogenic Climate Change. Bull. Am. Meteorol. Soc. 103, E936–E953. https://doi.org/10.1175/BAMS-D-21-0116.1
Zscheischler, J., Westra, S., Den Hurk, B.J., 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, 469–77.