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TOPICAL REVIEW

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, 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 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 (Trenberth *et al* 2015, Shepherd 2016, Otto 2017, Jézéquel *et al* 2018) and different methodologies (e.g. Pall *et al* 2011, Meredith *et al* 2015, Robin and Ribes 2020, Faranda *et al* 2022).

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 (Zscheischler and Lehner 2022, Qian *et al* 2023).

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 (Agha Kouchak *et al* 2015, 2021, 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. Wendt *et al* 2020, Ashraf *et al* 2021). 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 EEA 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 (Mitchell *et al* 2016, Frame *et al* 2020a, 2020b, Litzow *et al* 2021, Vicedo-Cabrera *et al* 2021, 2023), or on dynamical impact models, deriving impacts in both the factual and counterfactual worlds obtained from climate models (Schaller *et al* 2016, Sippel *et al* 2017, Sebastian *et al* 2019, Wehner and Sampson 2021, Smiley *et al* 2022). 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* 2017, 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, Selby *et al* 2017, Ribot *et al* 2020), 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), who quantified 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 (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 2020, 2023).

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 a technical adaptation strategy; 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

2.1. 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

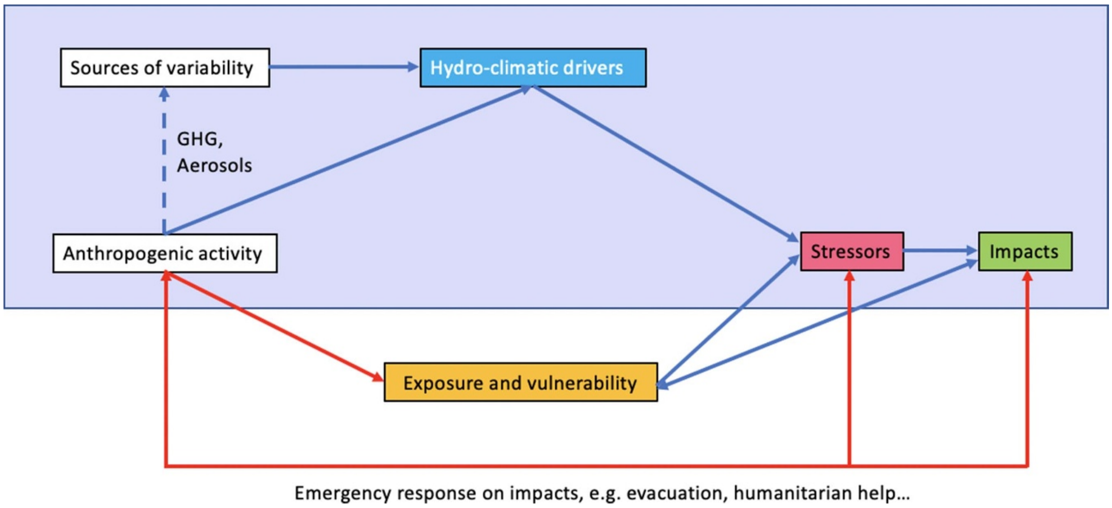

Figure 1. Conceptual framework for a broader attribution of disasters to human influence, adapted from Bastos *et al* (2023)'s framework of ecoclimatic events (figure 2 of their work). The blue frame corresponds to a traditional EEA framework, the red arrows are generally not considered in EEA studies.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

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.

2.2. The framework

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 (2020, 2023) 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 *et al* 2018, Zscheischler *et al* 2020).

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 (Goddard and Gershunov 2020), the Indian Oscillation Dipole, or the Atlantic Meridional Oscillation (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* 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 has 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.

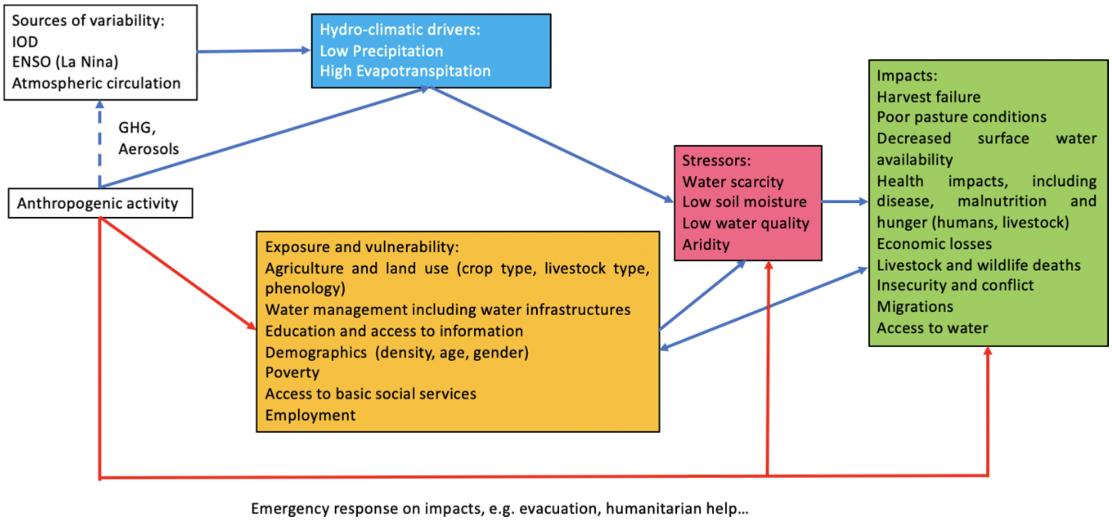

Figure 2. Causality chart for the 2021–2022 Kenyan drought. This is a partial causality chart based on information collected from academic literature and reports, which are detailed in the text. A more complete chart could be established in partnerships developed with subject matter and local expertise.

The 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.

3.1. Kenyan drought (2021–2022)

3.1.1. 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 2023). 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 9210 metric tonnes of food commodities had been distributed and Ksh. 1 billion (approx. US$ 7.29 million) cash-based transfers had been made (WFP 2023). This list of impacts is summed up in the green box of figure 2.

3.1.2. 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 n.d.), 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 season.

3.1.3. 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 2013, 2017), 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 *et al* (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.

3.2. The 2013–2015 marine heatwave in the northeast Pacific

3.2.1. 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 (Whitney 2015, Le Grix *et al* 2021, Wyatt *et al* 2022) caused significant changes in zooplankton and marine invertebrate populations (Leising *et al* 2015), 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.

3.2.2. 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

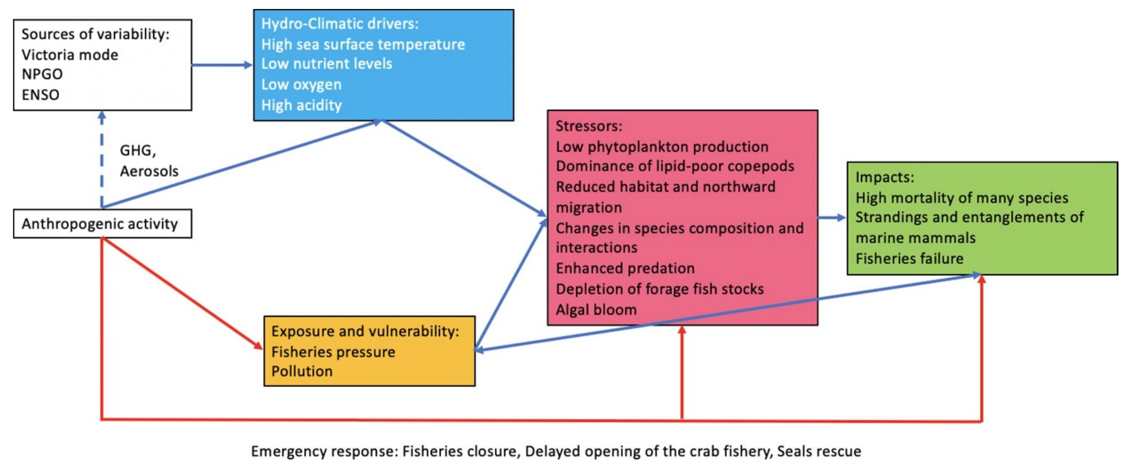

Figure 3. Causality chart for the 2013–2015 Pacific marine heatwave. The references used to fill each box are listed in the text. This is a partial causality chart, based on the literature listed in the text. A more complete chart could be established in partnerships developed with subject matter and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

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 *et al* 2015). 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).

3.2.3. 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 (Hazen 2018, Gissi *et al* 2019). 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.

3.3. Extreme fire season of 2017 in Portugal

3.3.1. 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

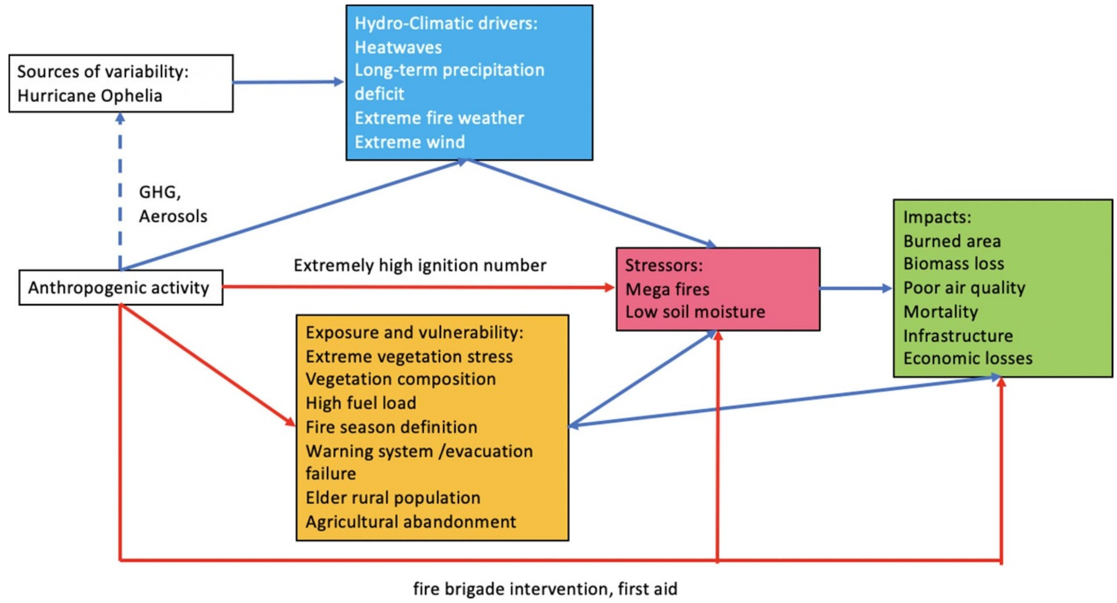

Figure 4. Partial causality chart for the October 17 fires in Portugal, based on Ramos *et al* (2023), and additional studies including additional socio-environmental factors listed in the text. A more complete chart could be established in partnerships developed with subject matter and local expertise.

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 24 h (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.

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 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 15 October, as described below.

3.3.2. 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 12 October onwards, transitioned to an extratropical storm. On 15 October 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 °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 50–80 km h^{-1}). 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).

3.3.3. Exposure, vulnerability, and human influence

3.3.3.1. 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).

3.3.3.2. Ignitions

The critical fire season considered by the Portuguese authorities was typically considered between July and September. The critical period was prolonged until 23 November, which imposed a prohibition of management fires in forest and agricultural areas (Libertà *et al* 2018). This is, however, a time of the year when fire is commonly used in local agricultural management practices. On 15 October, 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 10 000 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 facilitates the occurrence of very large and uncontrollable fires (Barros and Pereira 2014, Fernandes *et al* 2016, Benali *et al* 2021).

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.

3.4. Attribution of Acqua Alta events and evaluation of adaptation strategies

3.4.1. 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.

3.4.2. 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, as shown in figure 5) 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).

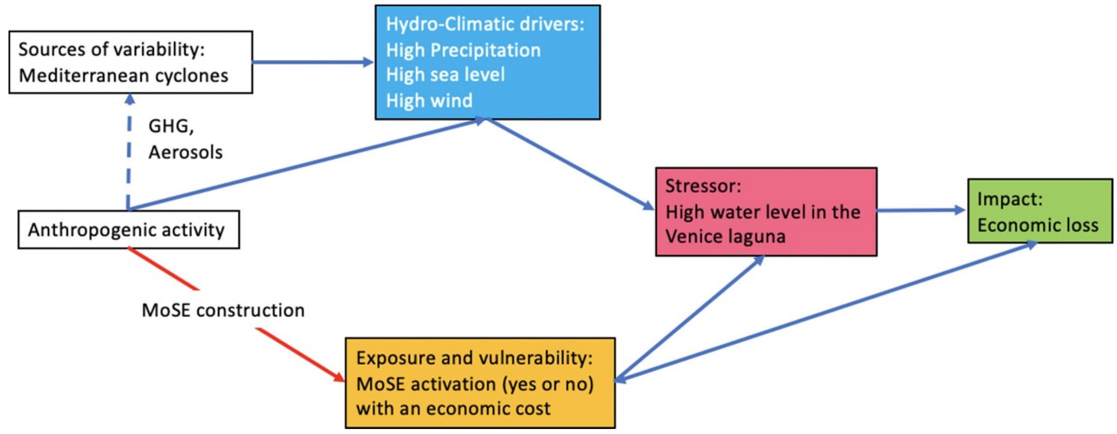

Figure 5. Partial causality chart for the Acqua Alta events in Venice modulated by the activation of the MoSE, describing the protocol used by Faranda *et al* (2023). Many impacts and most of the exposure and vulnerability are not addressed in this study.

3.4.3. 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 111 cm (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 Lewis and Kelman 2012, Katherine *et al* 2020).

3.5. The 2020 California drought and the FIRO system

3.5.1. 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 1200 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. Flint *et al* 2018, Delaney *et al* 2020). 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.

3.5.2. 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. Swain *et al* 2014, Diffenbaugh *et al* 2015, Williams *et al* 2015, Williams 2020). 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. Diffenbaugh *et al* 2015, Cheng *et al* 2016). 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 (Gershunov *et al* 2017, 2019, Swain *et al* 2018, Bevacqua *et al* 2022).

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. Funk *et al* 2014, Diffenbaugh *et al* 2015, 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 droughts 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 that '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 droughts, the influence on agricultural droughts is significant due to increases in evapotranspiration in a warmer climate. Presumably, this leads to increases in hydrological droughts as runoff is lower when soils are drier and have more capacity to store incoming precipitation (Sumargo *et al* 2021).

3.5.3. Human influence on exposure: the FIRO programme as an adaptation policy

The FIRO programme 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, and show the results in figure 7.

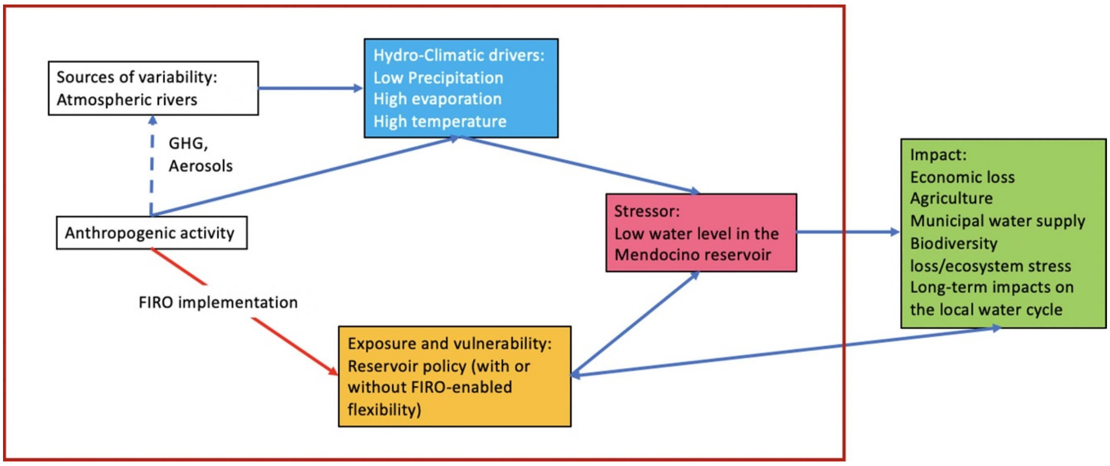

Figure 6. Partial causality chart for the 2020 California drought modulated by the use of the FIRO system. Here, we only discuss how to achieve a quantitative attribution of stressors, not impacts, and the causality chains inside the red box. Many impacts and most of the exposure and vulnerability are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

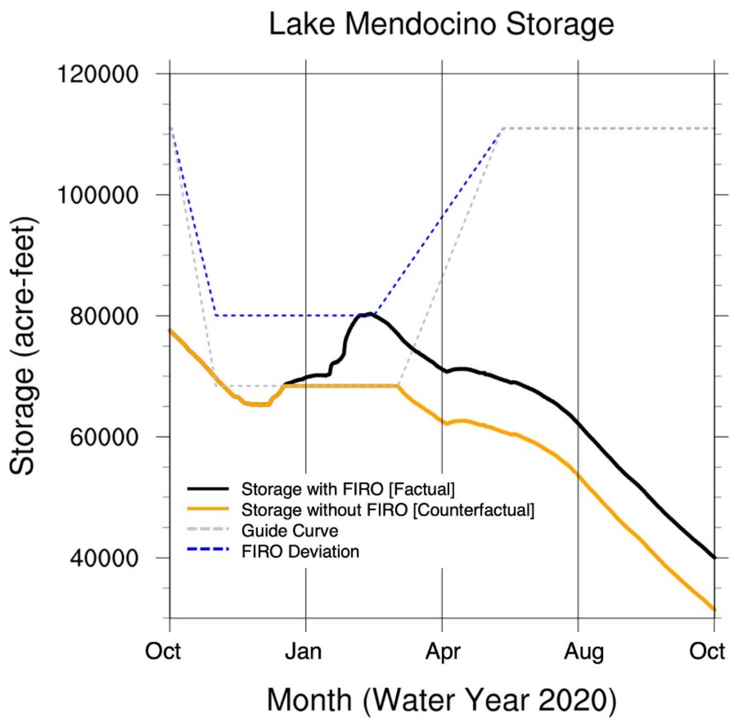

Figure 7. Storage and guide curves for Lake Mendocino during water year 2020, illustrating the factual (actual storage using the FIRO-enabled deviation (blue dashed line)) in the black curve, and the counterfactual (storage if the reservoir had been managed to the existing guide curve (grey dashed line)) 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 (figure 7).

Based on these first results, such a model could be used to compare Lake Mendocino's 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 (Lewis and Kelman 2012, Hore *et al* 2020).

4. Discussion

The case studies detailed above show several directions in which our framework could be used to expand EEA. We hope that this framework could help to shed light on shifting spaces for action in DRR 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 only 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* 2020), 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* (2011, 2014) 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* 2017 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 DRR. Paradoxically, by pushing for a climate justice agenda, EEA might participate in strengthening the focus on the hazard part of disasters and be blind to long standing social conflicts surrounding disaster reduction to focus DRR around social vulnerabilities (Hulme *et al* 2011, Grant *et al* 2015, 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.

Data availability statement

No new data were created or analysed in this study.

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