Scenarios of Human Responses to Unprecedented Social Environmental Extreme Events

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Scenarios of Human Responses to Unprecedented Social-Environmental Extreme Events

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Key Points:

- We conceptualize unprecedented extremes as social-environmental processes shaped by institutional, political, and economic change
- As social-environmental extremes become more frequent, there is an urgency to unravel their genesis and the possible societal responses
- This approach is the first building block of a new field of research in social-environmental extreme event forecasts

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Abstract In a rapidly changing world, what is today an unprecedented extreme may soon become the norm. As a result, extreme-related disasters are expected to become more frequent and intense. This will have widespread socio-economic consequences and affect the ability of different societal groups to recover from and adapt to rapidly changing environmental conditions. Therefore, there is the need to decipher the relation between genesis of unprecedented events, accumulation and distribution of risk, and recovery trajectories across different societal groups. Here, we develop an analytical approach to unravel the complexity of future extremes and multiscalar societal responses—from households to national governments and from immediate impacts to longer term recovery. This requires creating new forms of knowledge that integrate analyses of the past—that is, structural causes and political processes of risk accumulation and differentiated recovery trajectories—with plausible scenarios of future environmental extremes grounded in the event-specific literature. We specifically seek to combine the physical characteristics of the extremes with examinations of how culture, politics, power, and policy visions shape societal responses to unprecedented events, and interpret the events as *social-environmental* extremes. This new approach, at the nexus between social and natural sciences, has the concrete advantage of providing an impact-focused vision of future social-environmental risks, beyond what is achievable within conventional disciplinary boundaries. In this paper, we focus on extreme flooding events and the societal responses they elicit. However, our approach is flexible and applicable to a wide range of extreme events. We see it as the first building block of a new field of research, allowing for novel and integrated theoretical explanations and forecasting of social-environmental extremes.

Plain Language Summary The world is seeing increases in a range of extreme events, and this increase may continue or even accelerate in the future, due to anthropogenic climate change. Furthermore, it is often those who are already vulnerable that experience the biggest impacts from these extremes. Yet, there is little understanding of the possible societal responses to unprecedented events. This underscores the urgency of creating innovative approaches to develop plausible scenarios of societal responses and, in turn, mitigate hazards and reduce vulnerability and exposure to extreme events. In this commentary, we develop a truly interdisciplinary conceptual approach to better understand how different societal groups might interact with and respond to future unprecedented extreme events. We combine social science theories describing how different societal groups are affected by, and recover from, extreme events with projections from the literature identifying plausible areas at risk of unprecedented occurrences and local analyses of past extreme events. We see this as the first building block of a new field of research in forecasting social-environmental extremes that could support governments, civil protection agencies, and civil society organizations to ensure a fairer, improved response to future events.

1. Introduction

In a rapidly changing, human-dominated world, what is today unprecedented may soon become the norm (Aerts et al., 2014; AghaKouchak, Huning, et al., 2018; Blöschl, Hall, Viglione, et al., 2019; Ma et al., 2020; Marvel et al., 2019; Murray & Ebi, 2012). Human activities are triggering an increased number of landslides (Froude & Petley, 2018), while altered hydroclimatic conditions in the context of anthropogenic climate change are exacerbating extreme event occurrences and the associated hazards (Balch et al., 2020; Field et al., 2012). Numerical projections of future climates suggest that the latter trend is set to worsen in the

foreseeable future (Blöschl, Hall, Parajka, et al., 2017; Giorgi et al., 2018; Marvel et al., 2019), albeit with a large regional variability (Blöschl, Hall, Viglione, et al., 2019). This includes heavy precipitation events (Pfahl et al., 2017), devastating floods (Blöschl, Hall, Viglione, et al., 2019; Di Baldassarre et al., 2010), droughts (Marvel et al., 2019; Xu et al., 2019), and less obvious hazards such as flooding from heavy rain-on snow occurrences (Musselman et al., 2018). Similarly, widespread wildfires (Abatzoglou & Williams, 2016; Dennison et al., 2014) and unparalleled and prolonged heatwaves (Schiermeier, 2018; Vogel et al., 2019) are becoming more frequent and intense globally. The patterns of occurrence of these extreme events also reveal their interconnectedness, which can lead to more severe hazards than would be expected if the extremes were independent. For example, long periods of drought may be followed by wildfires, which in turn may increase risks of flooding and landslides (AghaKouchak, Huning, et al., 2018).

The above trends are expected to increase the likelihood and intensity of extreme-related disaster occurrences in many regions (Balch et al., 2020; Battisti & Naylor, 2009; Field et al., 2012; Gariano & Guzzetti, 2016). This will have profound implications on the ability of different societal groups to recover from and adapt to future extreme events. In many regions globally, the societal costs from extreme-related disasters are likely to be unevenly distributed and to affect the most those who are already more vulnerable (Adger, 2006; Collins, 2009; Cutter et al., 2003). Concurrently, the Anthropocene marks the recognition of the role of human beings in altering virtually all spheres of the Earth System, from the hydrosphere to the biosphere, atmosphere and lithosphere (AghaKouchak, Feldman et al., 2015; Castree, 2015; Himiyama, 2020; Lewis & Maslin, 2015; Rose & Cachelin, 2018). This evidence has urged scholars from different disciplinary perspectives to rethink extreme events in the Anthropocene as generated by interwoven social and environmental processes (Castree, 2015; Collard et al., 2018) or, in other words, as being social-environmental extremes (Balch et al., 2020).

While calls for examining extreme events as interwoven social and environmental processes proliferate (Balch et al., 2020; Biermann et al., 2016; Hackmann et al., 2014; Reid et al., 2010), and there is a vast scientific literature on potential unprecedented events, the recognition that the human and Earth systems are internally related did not translate into a widespread and deep engagement with critical social sciences. Conceptions of the human dimension that account for power, inequalities, and conflicting visions on socio-political and environmental regimes remain scant in examinations of extreme events (Castree et al., 2014; Rusca & Di Baldassarre, 2019). Moreover, disaster management studies have long been entrenched in disciplinary perspectives, dominated by behavioral and positivistic social sciences, and geophysical science (Hewitt, 1983; Pelling, 2001, 2010). Thus, depoliticized notions of the construction of disasters have prevailed in research attempting to gauge human responses to social-environmental extremes. These conventional approaches prevent from unraveling the genesis and local impacts of unprecedented extremes on different societal groups and the complex feedbacks they trigger. As a result, there is little understanding of the possible societal responses that future extremes will elicit. This underscores the urgency of creating a new knowledge base encapsulating the complexity of future interplays between society and environmental hazards from household to national government responses and from immediate impacts to differential long-term recoveries of distinct socio-economic demographics.

Here, we seek to address this major scientific gap by proposing a framework for developing scenarios of how different societal groups might interact with and respond to future unprecedented extreme events. We term this novel approach *Social-Environmental Extremes Scenarios Approach*. To develop and test this approach, we specifically consider extreme floods, as they can potentially affect every region of the world and are set to increase in magnitude, frequency and negative impacts (Blöschl, Hall, Viglione, et al., 2019; Di Baldassarre et al., 2010; Pfahl et al., 2017). However, our methodology is flexible and directly applicable to a wide range of social-environmental extremes. Drawing on wide-ranging disciplinary perspectives, we conceptualize unprecedented extreme events as social and environmental processes, tied to institutional, economic, and political transformations, and resulting in severe and often unequal social impacts (Balch et al., 2020; Castree et al., 2014; Collard et al., 2018).

To examine the physical characteristics of the extreme flood events, we draw on climate projections from numerical earth system models. These build on a set of socio-economic pathways and allow to both delineate the future physical space of our Planet and identify plausible, and geographically referenced, future occurrences of extreme events (Abatzoglou & Williams, 2016; Haarsma et al., 2016; Musselman et al., 2018;

Spence et al., 2011; Vogel et al., 2019). The analysis of societal responses draws on critical social sciences. In contrast to predominant examinations of the interplay between extreme events and society, our approach seeks to unravel key societal mechanisms, including the political economy of social-environmental extremes and the power dynamics underlying uneven development and vulnerabilities, as well as differentiated recoveries from extreme events at multiple scales.

2. Methods

2.1. The Social-Environmental Extremes Scenarios Approach

To develop the *Social-Environmental Extremes Scenarios Approach*, we first engage with theoretical perspectives that account for the ways in which power is held and mobilized in the construction of extreme-related disaster occurrences and recovery processes, eschewing technocratic and uncritical interpretations. We then rely on the event-specific scientific literature to identify locations that have a high risk of experiencing unprecedented events. For example, in the case of the extreme floods that we use to test our approach, we draw from the literature on numerical climate projections. Finally, we combine these with empirical studies on past events to develop plausible societal responses to future events of unprecedented magnitude. Our conceptual innovation consists in placing critical social science theories on vulnerability to social-environmental extremes, disaster risk and recovery trajectories in direct relation with plausible future events. We propose four Pillars to obtain this innovative, holistic vision:

1. Synthesize critical social sciences theoretical perspectives on the interplay between extreme events and societal responses, including responses at individual and household level (Section 3.1); the power relations underlying the construction of a disaster and the uneven distribution of costs and benefits (Section 3.2); and state-civil society relations in the aftermath of a disaster (Section 3.3). We also consider immediate responses to and long-term processes of recovery from extreme events. To conceptualize the multiple spatio-temporal scales and differential recoveries that constitute societal responses, we refer to *mutiscalar societal responses to extreme events*.
2. Leverage the event-specific literature to identify plausible, geographically referenced unprecedented events.
3. Consider past extremes of different magnitudes at the location of interest, and leverage these to infer possible responses in that same location to future extremes of unprecedented magnitude.
4. Consider past events at other locations which were of greater magnitude than the ones that occurred in the location of interest. Perform a conceptual transfer to infer possible responses to social-environmental extremes, which are unprecedented in the location of interest, but comparable in magnitude to those that occurred at the other locations.

By design, Pillar 1 is somewhat more general in scope than the other three, as it encompasses a number of theoretical perspectives applicable to a broad range of social-environmental extremes. Pillars 3 and 4, on the other hand, need to be tailored closely to the chosen type of event and its location, as determined in Pillar 2. These Pillars individually present serious limitations, but when leveraged collectively, they provide a new knowledge base functional to our goal of developing future responses and recovery trajectories from unprecedented events (see Figure 1, Social-Environmental Extremes Scenarios Approach). Some of these scenarios may already be emerging in current times, while others are plausibility hypotheses in humanity's future space.

2.2. Testing the Social-Environmental Extremes Scenarios Approach for Unprecedented Flooding

In the following sections, we outline and test our approach, which is flexible and applicable to a wide range of extreme events. We begin by synthesizing critical theoretical perspectives on multiscalar societal responses to extreme events (Pillar 1). We next select unprecedented floods as the extreme event of interest, and identify Houston, Texas, as a plausible location for future, unprecedented flooding (Pillar 2). To be able to test the effectiveness of our approach, we opt to perform a hindcast, as opposed to a forecast of a future, yet-to-occur extreme. We place ourselves in early 2017 and, using then-available information, we outline a scenario for unprecedented flooding in the area, which we know occurred later in that year following the

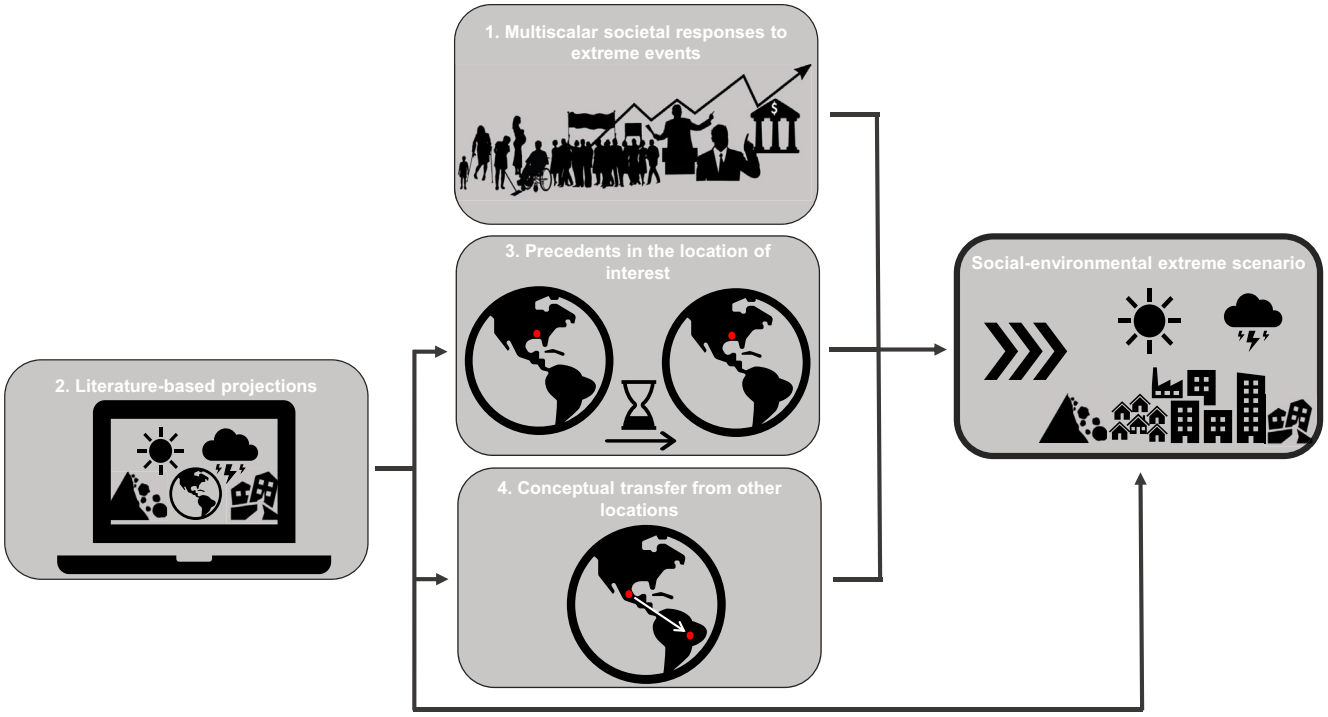

Figure 1. Schematic of the Social-Environmental Extremes Scenarios Approach. The approach rests on a synergy of literature-based projections, critical social science theoretical perspectives on multiscalar societal responses to extreme events, and effective use of data from past social-environmental extremes.

passage of Hurricane Harvey (Oldenborgh et al., 2017). For Pillar 3, we draw on Storm Allison and Hurricanes Rita and Ike, which led to severe flooding in Houston and the surrounding Harris County prior to 2017. For Pillar 4, we draw on Hurricane Katrina, which led to widespread flooding in New Orleans and elsewhere in 2005 and went down in history as the costliest and one of the deadliest storms in the United States (Knabb et al., 2005). We then combine these to outline a scenario for unprecedented flooding in Houston, and verify it using the flooding associated with Hurricane Harvey in 2017 (see Figure 2). While the hindcast serves to validate our approach, the method's potential lies in providing plausible scenarios of future responses to unprecedented extremes. We provide a brief practical example by developing a social-environmental extreme scenario of flooding in Miami, Florida, in Section 4.3.

To develop the case study analyses for Pillar 3 and 4 and the social-environmental extreme scenario of Miami, we undertook an integrative literature review (Torraco, 2016). Our integrative review combines studies from critical social sciences, economics, psychology, hydrology, and climatology to generate a new and integrated understanding of the multiple dimensions of social-environmental extremes and the societal responses they elicited in the selected case study areas. Based on the theoretical synthesis (Section 3.1), the following key aspects of societal responses to unprecedented events were identified and included in the review for the selected case studies: i. vulnerability and recovery trajectories; ii. disaster as human constructs; iii. practices of emancipatory and reactionary change in the aftermath of a disaster.

3. Building a Social-Environmental Extreme Scenario

We present here the different pillars needed to build a social-environmental extreme scenario (Section 2.1), tailored to the specific case study described in Section 2.1. The theoretical synthesis (Section 3.1) considers critical social science literature on disasters more broadly as several aspects discussed in these studies also apply to extreme-related disasters.

Figure 2. Testing the Social-Environmental Extremes Scenarios Approach on unprecedented flooding. To test our approach, we perform a hindcast of Hurricane Harvey-like flooding by combining theoretical perspectives on multiscalar societal responses to extreme events (Pillar 1) with numerical climate projections of Houston, Texas (Pillar 2). We draw on Storm Allison and Hurricanes Rita and Ike as precedents in the same location (Pillar 3) and on Hurricane Katrina for the conceptual transfer (Pillar 4). Photo credits: Pillar 1 © Jakartatravel/Adobe Stock; Pillar 2 © Lavizzara/Adobe Stock; Pillar 3 Adam Baker (Hurricane Ike. Hurricane Ike Water Line) CC Creative Commons; Pillar 4 Carol Colman/Pixabay; Pillar 5 © Irina K./Adobe Stock.

3.1. Pillar 1—Theoretical Synthesis of Mutiscalar Societal Responses to Extreme Events

3.1.1. Uneven Development Generates Differentiated Vulnerabilities and Recoveries

Uneven development is a key determinant of differential vulnerability and uneven distribution of disaster risk. There is a widespread consensus within social science scholarship that multiple dimensions of inequalities—class, gender, socio-economic status, race, and ethnicity—intersect in critical ways in the production of vulnerability to hazards (Adger, 2006; Bolin, 2007; Collins, 2010; Cutter et al., 2003; Enarson, 1998; Hewitt, 1983; Mustafa, 2005; Pelling, 2003). First, marginalized groups are often located in disaster-prone areas, and exposed to greater health, financial and livelihood threats from natural hazards. Higher income residents, on the other hand, mostly occupy safer grounds or may *opt* for hazardous locations if aesthetically and economically attractive and if vulnerability to the hazard can be externalized (through, e.g., insurance and/or flood control infrastructure) (Collins, 2009; Maldonado et al., 2016). Housing inequalities constitute another dimension of vulnerability that intersects with socio-economic and racial factors, with lower income and marginalized groups often renting or owning homes that are less likely to withstand extreme events such as floods and hurricanes (Fothergill & Peek, 2004; Van Zandt et al., 2012; Y.; Zhang, 2012). Moreover, education and age importantly shape the ability to access, understand and react to warnings. In emergencies, elderly people require additional support (Cutter et al., 2003), with lower income and non-white elderly more at risk (Finch et al., 2010; Fothergill & Peek, 2004; Ngo, 2001). For example, in the south-eastern United States lack of transport and affordable alternative refuge accommodation makes it challenging for lower income groups to evacuate following a hurricane warning (Peacock et al., 1997).

Importantly, vulnerability does not end with the occurrence of an extreme event (see Figure 3). Socio-political and economic inequalities that characterize societies *prior* to a disaster affect the ability of different societal groups to cope with and recover *from* a disaster (Adger, 2010; Elliott & Pais, 2006; Mustafa, 1998; Verchick, 2012; Wisner et al., 2004). Preexisting housing inequalities often protract housing recovery of lower income and marginalized residents (Peacock et al., 2014; Van Zandt et al., 2012). This is mostly due to the

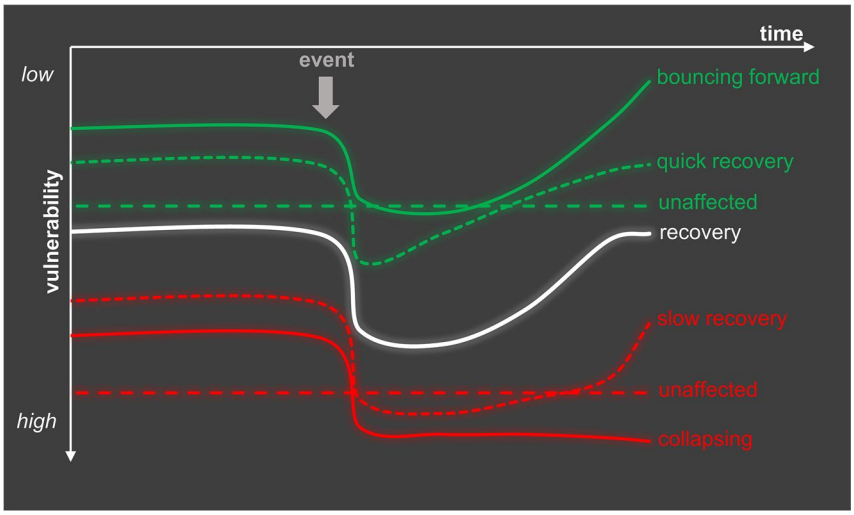

Figure 3. Differential recoveries from extreme events. The diagram depicts the differential recoveries over time concealed within a hypothetical mean societal *recovery* (white line) following an environmental extreme event (gray arrow). Social theories (Pillar 1) and empirical work (Pillar 3 and 4, and the Hindcast) indicated that groups with high vulnerability and exposure (in red) tend to *recover slowly* and may even *collapse*, while groups with lower vulnerability due to either low exposure or externalization of risk (in green) tend to *recover quickly* or *bounce forward*. The diagram also shows *unaffected* social groups whose vulnerability, because of little or no exposure, remains unchanged before, during and after the event.

fact that these social groups have limited access to capital, exiguous savings and hold poor or no insurance (Peacock et al., 1997; Y.; Zhang, 2012). In the United States, Afro-American and Hispanic residents were more likely to receive lower settlement amounts from insurance companies following flooding-related damage (Fothergill et al., 1999). Racial difference also takes the form of immigration status, with undocumented immigrants declining recovery assistance for fear of being deported (Fothergill et al., 1999).

Finally, social and psychological research supports a strong correlation between socio-economic status and psychological vulnerability (Fothergill & Peek, 2004). This includes disproportionate trauma of exposure to an extreme event and greater stress due to job loss in its aftermath. In particular, while salaried professionals are often able to maintain jobs and paychecks throughout the crisis, lower paid workers in the service sector are more likely to be unpaid (Fothergill & Peek, 2004).

3.1.2. Disasters Are Human Constructs

Disasters, often resulting from extreme events, have been characterized as constituted through human-environment interactions: vulnerability is produced *within* a place *by* a social system- or, in other words, disasters are human constructs (Adger, 2006; Hewitt, 1983; Pelling, 2010; Pelling & Manuel-Navarrete, 2011; Wisner et al., 2004). The exercise of power—both political, discursive, and economic—is integral to vulnerability, distribution of hazard risk, and societal responses to extreme events (Adger, 2006; Eriksen et al., 2015; Hewitt, 1983; Mustafa, 1998; Pelling, 2010). While power relations generating a disaster and social vulnerability may vary from place to place (Finch et al., 2010; Hewitt, 1983), scholarship has identified some consolidated patterns. It is widely recognized that the political economy of natural resources use is integral to the production of vulnerability to extreme events (Adger, 2000, 2006; Cutter et al., 2003; Davis, 1998; Mustafa, 1998; Pelling, 2001; Wisner et al., 2004). This is driven by the simultaneous and mutually constitutive processes of *marginalization*—that is, dispossession from resources and services to reduce exposure and cope with unprecedented extremes, and *facilitation*—that is, the institutional processes of resources concentration and capital accumulation that allow powerful actors to externalize risk (Collins, 2008, 2009, 2010). A rich body of literature has examined these recursive dynamics of "vulnerability-in-production" (Simon, 2014, p. 1,199) for floods (Collins, 2009, 2010; Pelling, 1999), including Hurricane Katrina (Bullard & Wright, 2009; Freudenburg et al., 2009; Horowitz, 2014; Savelli et al., 2021; Travis, 2005), and for other natural hazards (Collins, 2008; Mustafa, 1998; Sen, 1990; Simon, 2014) in different geographical contexts. These dynamics, Harvey (2007) has long argued, are the norm in neoliberal economies.

The same dynamics are integral to institutional responses to extreme events. First, the structure of recovery funding has systematically advantaged middle-class homeowners (Fothergill & Peek, 2004; Peacock et al., 2014). Second, post-disaster reconstruction efforts are often turned into for-profit endeavors that aggravate the vulnerability of the most affected populations (Gunewardena, 2008; Klein, 2007; Schuller & Maldonado, 2016). Globally, strategies of capitalizing on disasters have taken the form of enclosures (i.e., the transfer of public assets to the private sector) (Arena, 2011; Klein, 2007), no-bids reconstruction contracts for corporate for-profit entities (Gunewardena, 2008; Schuller & Maldonado, 2016), land grabs, evictions, or eradication of public housing that prevent residents from returning (Gunewardena, 2008), prioritization of high-end developments at the detriment of local livelihoods (Stonich, 2008), and co-optation of relief funding by state and private actors (Pelling, 1999).

3.1.3. The Transformative Potential of a Disaster?

The aftermath of a disaster can drive a range of dynamics, from transformative change to top-down repressions or acceleration of the pre-disaster trajectories (Adger, 2010; Gawronski & Olson, 2013; Pelling & Dill, 2010). On the one hand, disasters can constitute a "critical juncture" (Olson & Gawronski, 2003) or "tipping point" (Pelling & Dill, 2010) and catalyze the emergence and legitimation of new political actors; increased mobilization and empowerment of civil society (Cretney, 2019; Luft, 2009; Pelling & Dill, 2010); or new modes of (hegemonic) governance (Venugopal & Yasir, 2017; Wainwright & Mann, 2013). For instance, following the 1972 earthquake, Nicaragua shifted from an authoritarian regime to a quasi-democratic system, influenced by Marxist principles (Olson & Gawronski, 2003). This shift is attributed to the government's mishandling of the recovery from the earthquake, which ultimately led to political pluralism, empowerment of civil society and social mobility (Olson & Gawronski, 2003). To a lesser extent, a social mobilization of marginalized groups was also seen in the aftermath of Hurricane Andrew, which affected Florida and Louisiana in 1992 (Fothergill et al., 1999). On the other hand, repression of emerging social movements, proclamation of "state of exception" or martial law and human rights violations to "protect" state institutions have been a common response to extreme events globally, albeit primarily in authoritarian regimes (Gawronski & Olson, 2013; Pelling & Dill, 2010; Seekins, 2009). In democratic regimes, governmental counterthrust mostly takes the form of reactionary politics rather than outright repressions (Albala-Bertrand, 1993; Drury & Olson, 1998; Wainwright & Mann, 2013), as also seen in the aftermath of Katrina (Arena, 2011; Bullard & Wright, 2009; Klein, 2007). Social stability and control in the aftermath of disasters are often insured through discursive capture and control over the memory of the disaster, including reassuring affected communities, deflecting attention from the most affected areas, managing criticism and constructing a narrative that emphasizes the extraordinary nature of the disaster, rather than political responsibilities of those in power (Ullberg, 2013; Williamson, 2018).

The effectiveness of social groups to challenge state and market forces and bring about structural changes are highly context-specific, but may be broadly schematized in terms of levels of social capital (Adger, 2010; Pelling, 2003; Pelling & High, 2005) and the extent to which it is supported by discursive (hegemonic ideas) and material resources (financial resources, housing, land tenure) (Adger, 2010; Drury & Olson, 1998; Pelling & Manuel-Navarrete, 2011). Some suggest that only the synergy between a "well-functioning" state (i.e., promoting security and sustainability) and high levels of social capital (i.e., internal and external networking) can significantly reduce vulnerability to extreme events (Adger, 2010) (see Figure 4). A weak/dysfunctional (coercive, illegitimate, absent or ineffective) state with low levels of social capital will increase conflict, poverty and in turn, undesirable conditions (e.g., famine) even in the absence of extreme events. A strong/well-functioning state with low levels of networking social capital or a weak/dysfunctional state with high levels of social capital can only ensure a certain degree of protection of marginalized groups (Adger, 2010). In the aftermath of Katrina, the response of state and civil society actors was not synergetic. Rather, social movements challenged state and market forces attempts to capitalize on the disaster by unsettling racial and housing politics, as well as the idea of "natural" disaster (Ishiwata, 2011; Luft, 2009), ultimately with limited long-term impacts.

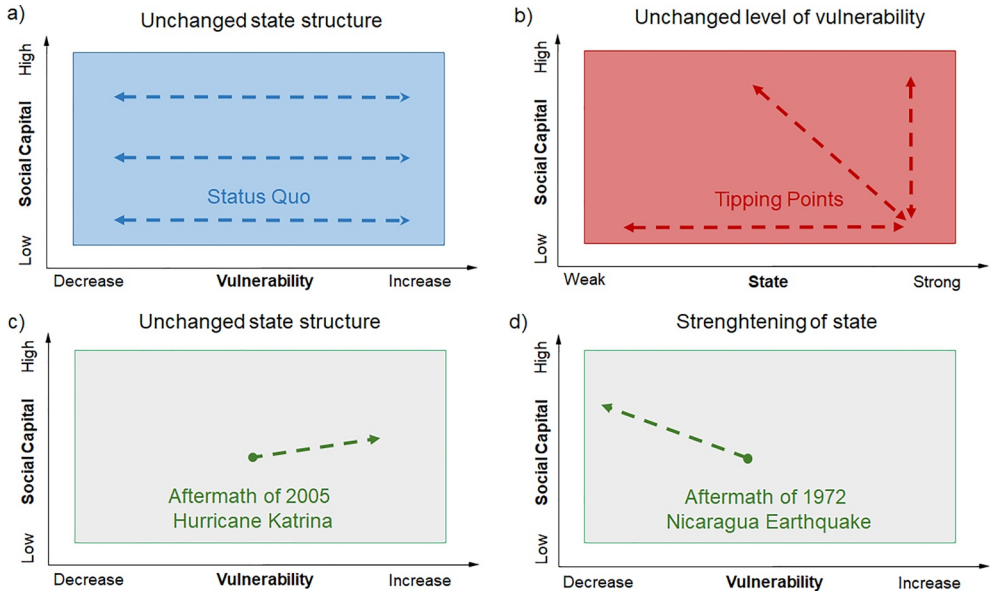

Figure 4. Social capital, state and vulnerability. Examples of socio-political trajectories in the aftermath of a disaster. (a) The blue plane and vectors illustrate status-quo trajectories, where pre-disaster political and economic structures are preserved and there are no appreciable social initiatives. Depending on the pre-disaster situation (weak/dysfunctional vs. strong/well-functioning state, high vs. low levels of social capital), the socio-political trajectory may lead to increased or decreased vulnerability (see Adger, 2010). (b) The red plane and vectors show "tipping point" trajectories, leading to large social, political or combined socio-political changes (Pelling & Dill, 2010). Tipping points may encompass both reactionary or progressive transformations. For clarity, in the panel we do not consider the vulnerability dimension; in practice, one may expect "tipping points" to affect the level of vulnerability. Schematic trajectories for (c) Katrina and (d) the Nicaragua Earthquake. Katrina fostered social movements with limited impact, and hence a limited increase in social capital. Pre-Katrina economic and political strategies were preserved, and these two factors exacerbated vulnerability. On the contrary, the Nicaragua Earthquake (1972) occasioned wider transformations with a strong increase in social capital, the emergence of a stronger and more democratic state and, arguably, a decrease in vulnerability.

3.2. Pillar 2—Climate Projections Support the Occurrence of Unprecedented Flooding in Houston

We next consider records of past flooding and climate projections to identify locations with a high risk of experiencing unprecedented flooding. Based on a review of the literature, we identify Houston and Harris County as one such location. As discussed in Section 2.2, to test our approach on a hindcast, we place ourselves in 2017 and only base our Pillar on then-available information.

Over the past 50 years, Harris County has been one of the U.S. jurisdictions most affected by floods due to heavy precipitation, both in terms of property damage and human life losses (Highfield et al., 2013) (see also Pillar 3 below). However, prior to 2017, the area had never experienced flooding on the scale of, for example, that caused by Hurricane Katrina in New Orleans in 2005. Up to 2017, at least four Hurricanes or Tropical Storms had brought precipitation locally in excess of 1,000 mm to Texas, although not in Houston (Tropical Cyclone Point Maxima, 2020). The climate projections available in 2017 pointed to future systematic increases in the magnitude of extreme precipitation events in the Houston area (Brouillette et al., 2012), increases in Hurricane potential intensity across the Gulf of Mexico (Balaguru et al., 2016), and increases in precipitation associated with Atlantic Hurricanes (Knutson et al., 2013). It was—and is—impossible to produce skillful deterministic forecasts of regional hydroclimatic extremes on climate timescales. However, one may argue that, based on then-available knowledge, in the years prior to 2017, it was reasonable to expect that Houston would experience future, unprecedented flooding driven by heavy rainfall with a higher likelihood than what at the time would have been suggested by applying extreme value statistics to historical rainfall data. With a stretch of the imagination, one could further have taken the most extreme precipitation from Hurricanes or Tropical Storms elsewhere in Texas as a plausible lower bound for what could have been expected in a generic, future unprecedented flood in Houston.

3.3. Pillar 3—Storm Allison and Hurricanes Rita and Ike: Harbingers of Bigger Floods to Come

Having established that, in 2017, it was reasonable to consider Houston and Harris County to be prone to unprecedented flooding, we consider past extreme floods in the area and leverage Pillar 1 to extract insights relevant to then-unprecedented future floods. We specifically focus on Storm Allison and Hurricanes Rita and Ike.

In 2001, Storm Allison caused extensive property damage to over 70,000 structures, 22 fatalities and overall damages for over 5 billion USD (Harris County's Flooding History, n.d.). More recently, Hurricanes Rita (2005) and Ike (2008) generated over 29.5 billion USD in damage, most of which was concentrated in the Houston metropolitan area (Highfield et al., 2013). Importantly, almost 50% of the total claims were outside the 100-year floodplain area, pointing to the inefficacy of this regulatory instrument in guiding urban planning, mitigating risks of exposure to floods and ensuring effective emergency responses (Highfield et al., 2013). Consistently with the multiscalar societal responses discussed in Pillar 1, in Greater Houston there is a clear correlation between socio-economic inequalities, minority residents, hazardous areas and lower-valued homes (Highfield et al., 2014). Following the above extreme events, racial minorities (African-Americans and Hispanics) experienced higher relative losses in terms of housing and longer recovery trajectories (Highfield et al., 2014; Peacock et al., 2014; Van Zandt et al., 2012). Moreover, in the aftermath of Ike, the number of public housing facilities was reduced, further exacerbating the vulnerability of minority groups (Hamideh & Rongerude, 2018). Here, the demolition of four of the largest public housing developments in favor of more profitable commercial housing was promoted by stigmatizing public housing (Hamideh & Rongerude, 2018). The reconstruction efforts following Hurricanes Rita and Ike reiterated the risk of neoliberal responses to unprecedented extremes in a highly unequal society. To illustrate, in the case of the severely damaged power grids, private companies refused to embark in long-term infrastructural investments undermining short-term profits, passed on the costs of rehabilitation to customers through increased bills, and disregarded long-term risk reduction and the social costs to the most vulnerable (Miller et al., 2011).

3.4. Pillar 4—Conceptual Transfer: Learning from Hurricane Katrina

We next analyze the extreme flooding in New Orleans related to Hurricane Katrina, which at the time of occurrence was far more severe than any flooding experienced in Houston and Harris County. Furthermore, it affected an area with a broadly similar social, economic, and political mesh to Houston and Harris County. Although Houston has been mainly affected by precipitation-driven flooding, while Katrina's impact was largely due to storm surge and levee breaching, we nonetheless expect to be able to draw valuable information from a socio-economic and political standpoint.

Hurricane Katrina is considered the most destructive extreme event in the United States in modern times, with nearly 2,000 lives claimed, over 200,000 homes destroyed, and an estimated total damage of 161 billion USD (Blake & Zelinsky, 2018; Knabb et al., 2005). Approximately 260 km^2 of New Orleans' metropolitan area were flooded, with some neighborhoods under 4 meters of floodwaters (Jonkman et al., 2009). Concurrently, storm surge caused an extraordinarily large release of industrial toxic and hazardous chemicals, which mixed with floodwaters and generated the most significant contamination event in U.S. contemporary history (Picou, 2009; Santella et al., 2010). Over a quarter of New Orleans' population was displaced and, as of 2013, a third of the displaced people had not returned (Deryugina et al., 2018).

The impacts of Hurricane Katrina in New Orleans are illustrative of the relationship between class, gender, ethnicity and vulnerability (Pillar 1). Here, historic processes have coalesced to produce racial and class segregation, with low-income and minority neighborhoods significantly more exposed and vulnerable to flood events (Elliott & Pais, 2006; Finch et al., 2010). Indeed, the most severe flooding and the most devastating impacts of Hurricane Katrina occurred in low-income, Afro-American neighborhoods, such as the Lower 9th Ward in the St. Bernard bowl area (Elliott & Pais, 2006; Finch et al., 2010; Jonkman et al., 2009; Kates et al., 2006). As a result, a significantly higher percentage of African-American were still exposed to floodwaters a week after Katrina (Morse, 2008). Here, the impacts of severe and long-term flooding were further aggravated by the fact that dwellers often own or rent mobile or stick homes that are more vulnerable to flooding. Moreover, they rarely have access to transport to evacuate (Masozera et al., 2007). Last, a large part

of the toxic and industrial sites of New Orleans are located in these flood-prone neighborhoods, which were significantly more affected by these hazards (Godsil et al., 2009; Morse, 2008).

The relationship between vulnerability to hazard *prior* to a disaster and differentiated recovery trajectory *from* a disaster (Pillar 1) holds true for New Orleans. Less vulnerable and less flooded affluent areas recovered faster than lower income ones, and income inequalities were exacerbated (Finch et al., 2010; Green et al., 2007). In short, vulnerable groups suffered greater relative economic losses and took more years to recover financially and psychologically from the disaster (Bates & Green, 2018; Bullard & Wright, 2009; Weil et al., 2018). Furthermore, Afro-American workers were four times more likely than white workers to lose their job in the aftermath of Katrina (Elliott & Pais, 2006) and the very structure of recovery funding created several barriers to access for lower income groups (e.g., waiting time, calculation of the grant) (Green et al., 2007). Ultimately, the same authors suggest, the lack of a clear commitment of the government to support reconstruction for lower income residents, the delayed repayments from private lower-cost insurances, the lack of affordable housing and job opportunities and gentrification prevented most vulnerable evacuees from returning to New Orleans.

Crucially, several studies suggest that the political economy of pre-Katrina New Orleans has actively increased the vulnerability to extreme events of the most marginalized groups (Bullard & Wright, 2009; Freudenburg et al., 2009; Horowitz, 2014; Travis, 2005) (Pillar 1). The "growth machine" of New Orleans consisted of gas and oil extraction and large-scale water projects (dams, levees and 15,000 km of transportation canals in the marshes) that generated a considerable loss of wetland and worsened the city's exposure to hurricanes (Freudenburg et al., 2009; Horowitz, 2014; Kates et al., 2006; Olshansky & Johnson, 2017; Travis, 2005). Alongside this environmental history, decades of public disinvestment in an increasingly racially segregated city with impoverished neighborhoods exacerbated differential vulnerability to extreme events (Bullard & Wright, 2009; Horowitz, 2014; Katz, 2008). In other words, the consequences of an extreme event ended up affecting most those who had benefited the least from the "growth machine" (Freudenburg et al., 2009).

Following Katrina, this unequal growth model was accelerated rather than adjusted, further exacerbating the vulnerability of the most affected to future extreme events. Residents were faced with closures of public schools and public housing (Arena, 2011; Bullard & Wright, 2009; Klein, 2007), erosion of worker protection with the suspension of the Davis-Bacon Act on minimum wage and work safety (Button & Oliver-Smith, 2008), the subjugation of (mostly Black and Hispanic) low-wage workers (Keegan, 2020), discriminatory treatment of undocumented workers (Button & Oliver-Smith, 2008), and no-bid contracts for corporations close to the government (Klein, 2007; Schuller & Maldonado, 2016).

Lastly, President Bush and Secretary of the U.S. Department of Homeland Security Chertoff constructed a narrative of unpredictability, with the former claiming that "none could anticipate the breach of the levees" (Parker et al., 2009). However, the possibility that a hurricane could generate major damage to New Orleans was well known amongst researchers and emergency practitioners (e.g., Travis, 2005). The success of social movements to produce counter-hegemonic discourses and politics was mixed. Post-Katrina social movements did not transform racial and housing politics in the United States, but they did unsettle it by producing a new discourse and political imaginary (Ishiwata, 2011; Katz, 2008), and by rejecting the exceptionalism of the disaster and placing it in the wider context of structural inequalities in the United States (Katz, 2008; Luft, 2009).

4. A Social-Environmental Extreme Scenario for Flooding in Houston

4.1. Houston is Underwater?

Hurricane Harvey hit Texas on 25 August 2017, bringing unprecedented flooding to Houston and Harris County. Based on the information available prior to that date, as summarized in our four Pillars above, could one have hypothesized an extreme event comparable to Hurricane Harvey, and have predicted its socio-economic impacts?

As outlined in Pillar 2, in 2017 it was not unreasonable to expect that an unprecedented flood in Houston had a higher likelihood of occurring than what could be inferred from historic climate data. A synergistic

application of our four Pillars using information available prior to 2017 suggests that unprecedented, extensive flooding will unevenly affect Houston residents. Past, smaller floods in greater Houston have revealed a close correlation between socio-economic status, race and exposure to extreme events (Highfield et al., 2014). Hispanic residents—especially immigrants—and other minority households are much more likely to inhabit 100-years flood zones, while more mitigation measures are undertaken in areas outside these zones (Maldonado et al., 2016). The same study also shows a significant correlation between income and exposure to floods. Race, socio-economic status and citizenship, therefore, will be key determinants of vulnerability to unprecedented flooding.

As suggested by Pillars 1 and 4, there is a correlation between the impacts of extremes, reduced public expenditure, economic model and differentiated social vulnerability. Houston's laissez-faire politics, based on planning deregulation, free entrepreneurism, low taxes and public disinvestment, benefitted elites and, in the long-term, exacerbated inequalities, environmental degradation and flood risks (Harper, 2004). One of the outcomes of this economic model are the mixed residential-industrial developments, mostly inhabited by minority groups. Both older (Bullard, 1983) and more recent studies (Collins, Grineski, Chakraborty, Montgomery, & Hernandez, 2015; Harper, 2004) have described Houston as a case in point of environmental injustice, highlighting how predominantly Hispanic and Black neighborhoods with a low percentage of homeowners are significantly more exposed than other areas to acute and chronic pollution and chemical spills. A recent analysis of risks of chemical spills during storms warned that these have substantially increased since the 1970s and that communities living in at risk census tracts (i.e., along the Houston Ship Channel) have become more racially segregated, poorer and, in turn, more vulnerable (Bernier et al., 2017; Linder et al., 2008). We expect the physical and environmental abandonment of low-income and minority neighborhoods to significantly shape their vulnerability to unprecedented flooding. Moreover, based on Pillar 3 and Pillar 4, petrochemical contamination with disparate residential and livelihood impacts on marginalized groups should be expected in Hurricane-induced disasters in Houston.

A second outcome of the Houstonian development model are the low-density developments, over 500 highways and several large parking areas that signal a heavy reliance on private transport (Harper, 2004). This urban fabric generated extensive wetland degradation, expansion of impervious surfaces, reduced rainfall infiltration and, in turn, greater exposure to flood risks (Blessing et al., 2017; S. Brody et al., 2014). Moreover, the City of Houston Housing and Community Development Department (Rackleff, 2015) warned that low-income neighborhoods lack key infrastructure such as storm and water drainage, despite occupying low lying, flood-prone areas. Based on this and on past floods in Harris county (Pillar 3), we foresee that unprecedented future flooding will largely occur outside the 100-years floodplain area, and will be more extreme in low-income and racially segregated neighborhoods, occupying lower grounds. As such, marginalized groups will suffer greater health, financial and livelihood losses.

In 2015, affordable housing across the city was identified as the highest concern in Houston, with minority, foreign-born and low-income households experiencing affordability challenges (costs above 30% of monthly income), overcrowding and, less frequently, incomplete kitchen facilities and plumbing (Rackleff, 2015). We expect housing to be a critical factor in determining one's recovery trajectory and ability to return home and rebuild. Faced with unprecedented flooding, racial minorities will receive lower settlements or have no insurance, and limited access to capital to return and rebuild. This will add to the already disproportionate post-traumatic stress of the extreme event, particularly felt by those most affected.

Houston's history reveals that its pro-growth model is deeply rooted and entrenched. Based on responses to past flood events in Harris County (Pillar 3) we expect that, in the aftermath of unprecedented flooding, Houston will retain its unequal growth model. Public disinvestment will continue and will aggravate the crisis of affordable housing as flooded complexes will not be renovated or will be transformed into more profitable estates. Local and national authorities will work toward a narrative of unprecedentedness to deflect attention from political responsibilities. The flooding will not trigger a transformation of the pre-existing political and economic structures, but will lead to emergence or transformation of new and social learning for movements and civil society organizations, that will incrementally strengthen their ability to trigger change.

4.2. Validating the Hindcast: Scenario Versus Reality

4.2.1. Hurricane Harvey: An Unprecedented Extreme With Major Socio-Economic Impacts

Hurricane Harvey will go down in history for the associated rainfall extremes and for the subsequent widespread flooding. The rainfall totals from the 25th to the 30th of August 2017 reached unprecedented levels for a tropical cyclone in the contiguous United States: just to the west of Houston a station recorded an accumulated value exceeding 1,300 mm, while a station in Houston logged almost 1,000 mm over a 3-day period (Oldenborgh et al., 2017). Never before had all 22 bayous and main channels spilled over at the same time, exposing Harris County to severe flooding risk (Sebastian et al., 2017). On August 27 several freeways in Houston were flooded, significantly affecting rescue operations. One day later, the Addicks and Barker reservoirs, designed to protect downtown Houston, were opened to avoid upstream flooding and damage to the dams. This, however, exacerbated downstream flooding with approximately 4,000 homes affected (Fitzpatrick & Spialek, 2020; Sebastian et al., 2017). The official report by Harris County Flood Control District (Lindner & Fitzgerald, 2018) documents 68 fatalities statewide, of which 36 occurred in Harris County, and approximately 154,170 homes flooded (of which 96,410 in Houston). It estimated damage caused by flooding across the Houston metropolitan area at 125 billion USD, making it the second costliest storm after Hurricane Katrina (2005) in U.S. history (Blake & Zelinsky, 2018).

Over 60% of the flooding associated with Hurricane Harvey occurred outside the 100-year floodplain area (HCDD & NALCAB, 2018). However, the impacts from Harvey were not as even-handed as the widespread flooding could suggest. Tracts that were more severely affected by flooding were inhabited by a significantly higher percentage of Black, Hispanic, and other minorities, as well as lower income households and people with a disability (Chakraborty, Collins, & Grineski, 2018, Chakraborty, Grineski, & Collins, 2019; Collins, Grineski, Chakraborty, & Flores, 2019; Fitzpatrick & Spialek, 2020). Compared to higher income residents, lower income households recorded almost twice the house or apartment damage, due to the structurally poor housing quality and the disproportionate exposure to Harvey-induced flooding (Chakraborty, Collins, & Grineski, 2018; Fitzpatrick & Spialek, 2020). Moreover, elevated exposure to flooding and industrial encroachment also led to disproportionate contamination from toxic spills from plastic and chemical plants and oil refineries (Bodenreider et al., 2019; Flores, Castor, et al., 2020; Horney et al., 2018; Stone et al., 2019). Manchester was one of the most affected neighborhoods along the Houston Ship Channel. Within 1 mile of this neighborhood, mostly inhabited by Hispanic (90%) and African-American (6%) households, are most of the city's facilities producing hazardous wastes (Horney et al., 2018).

In the aftermath of Harvey, racial minorities and lower income households were significantly more likely than average to experience inadequate access to—among others—drinking water, appropriate accommodation, food, electricity, transportation, and access to healthcare (Flores, Collins, et al., 2020). Non-citizen Hispanic residents suffered from even greater deprivations, confirming that citizenship is a key determinant of vulnerability. Moreover, a study on near-term recovery highlighted that while aid was—in most cases—disbursed to the most vulnerable social groups, this did not translate in effective near-term household recovery for lower income groups (Griego et al., 2020). Near-term recovery, the study suggests, was constrained by the limited capacity of lower income households to meet recovery demands. To access FEMA's relief funding, residents are required to have insurance. Yet many were unaware of this or unable to pay (Vinik, 2018). For others, the funding received was insufficient to repair and rebuild, leading to a prolonged semi-homeless condition (Fernandez, 2018). Similarly, some low-income home renters were faced with the unwillingness of landlords to invest in rehabilitating flood-damaged homes (Fitzpatrick & Spialek, 2020). A year after Harvey, the poorer neighborhoods were facing a slow recovery process, while middle-income residents had mostly recovered. In Kashmere Gardens, for instance, where 2/3 of the 11,000 residents are Black with an average annual income of 23,000 USD, some families still lived in flood-damaged homes, tents and trailers or with friends or family one year after Harvey (Fernandez, 2018; Vinik, 2018). Furthermore, in some low-income neighborhoods the increase in rental prices and housing value appreciation in the aftermath of Harvey exacerbated the preexisting affordable housing crisis, leading to increased homelessness and slow repatriation. Price appreciation and displacement were mostly faced by low-income residents in neighborhoods that did not flood (HCDD & NALCAB, 2018).

Hurricane Harvey has been described as a "quintessentially American tale" that called into question both Houston's unsustainable urban and economic growth and the "upbeat, pro-business strategy of low taxes

and little government" (Kimmelman, 2017). Indeed, Harvey's most significant environmental health impacts were directly correlated with preexisting industrial developments in Harris County (see above), and the city's unregulated urban growth, which exacerbated both storm rainfall and flood response (Sebastian et al., 2017; W. Zhang et al., 2018). Emblematic of Houston's unregulated development are the 14,000 homes constructed in the floodplain of the Addicks and Barker reservoir (Ross, 2019). Here, USACE only owns the land within the 100-year floodplain, while housing developments mushroomed in the private land surrounding it. Neither public officials nor private developers had an obligation to disclose potential flood risks of the area. During Harvey, over 5,000 of these homes were flooded.

Government officials have constructed a narrative of unpredictability to deflect political responsibilities. Trump tweeted his surprise ("Wow") and described Harvey as "epic" and "historic." This narrative is pushed forward despite the increasing evidence around the growing magnitude and intensity of extreme precipitation events in the region (e.g., Brouillette et al., 2012).

4.2.2. Validating the Scenario Using Hurricane Harvey

Our hindcast of Hurricane Harvey-like flooding provides an overall accurate representation of the events. On the one hand, Hurricane Harvey holds the rainfall record for a tropical cyclone in the contiguous United States, and rainfall totals for Houston and its surroundings were locally unprecedented. On the other hand, precipitation values comparable to those observed in Houston had been previously logged elsewhere in Texas as a result of past Hurricanes or Tropical Storms (Tropical Cyclone Point Maxima, 2020). Second, ex-post numerical simulations found that anthropogenic climate change favored Harvey's extreme precipitation, in line with the climate projections available prior to Harvey's occurrence (Trenberth et al., 2018). The flooding experienced in Houston during Hurricane Harvey was extreme, and may be taken as emblematic for an unprecedented precipitation-driven flood in the South-Eastern United States. At the same time, as discussed above and in Pillar 2, one may argue that the occurrence of Harvey in a climate-timescale, probabilistic perspective should not have been entirely surprising.

Many of the above-listed socio-economic impacts of Hurricane Harvey match closely those we hindcasted, since they may be traced back to preexisting conditions in Houston and Harris County. In particular, the worst-affected demographics, the differential near-term and longer term recovery across socio-economic groups, and media narrative following the extreme event reflect closely our inferences. Moreover, it was evident from Houston's history that release of toxic materials following flood events was a possibility, especially in low-income minority neighborhoods where industrial facilities are concentrated (Bodenreider et al., 2019; Collins, Grineski, & Chakraborty, 2018). Whist we were unable to predict the exact location of toxic releases, our hindcast did suggest that spills would occur and that impacts would be unevenly distributed. However, our hindcast also suggests that other dimensions of societal responses to extreme events can only be forecasted with little (or no) accuracy. For example, while an impact on housing markets and affordable housing was expected, our hindcast did not foresee that low-income neighborhoods outside the flooded area would be particularly at risk of gentrification. This would have required (amongst others) knowledge of the spatial distribution of flooding and of the impact of flooding across the city.

Depending on the chosen location, similar difficulties may extend to Pillar 2, when hypothesizing the form and immediate causes of flooding. In our case, precipitation-driven flooding had been the dominant flood risk in Houston prior to 2017, a pattern which was mostly confirmed by Harvey. However, the opening of the reservoirs, which aggravated the flooding, would have been very difficult to predict in our climate projection perspective. The transformative potential of hurricane Harvey was equally difficult to predict. Katrina had shown that catastrophic socio-economic impacts may not lead to a "tipping point." Similarly, in the aftermath of Harvey, Houston seems to have retained its economic model, with Trump's pledge to roll back on regulations, including building standards, planning and flood control (Sorkin, 2017). Indeed, notwithstanding a revision of the official flood maps, new developments have mushroomed in flood-prone areas of Houston (Ross, 2019). Last, the capacity of emerging or existing social movements to transform development and risk trajectories is dependent on multiple context-specific factors (e.g., type of political regime, social capital, emerging networks) and its impacts may not be immediately evident (Fitzpatrick & Spialek, 2020). We thus conclude that, while a civil society response is expected, its form and impact across different socio-temporal scales is particularly difficult to gauge.

Figure 5. Social-Environmental Extremes Scenarios of Miami, Florida. To develop our scenario, we combine theoretical perspectives on multiscalar societal responses to extreme events (Pillar 1) with numerical climate projections of Miami, Florida (Pillar 2). We draw on Hurricane Andrew (1992) and Hurricane Irma (2017) as precedents in the same location (Pillar 3) and on Hurricane Katrina for the conceptual transfer (Pillar 4). Photo credits: Pillar 1 © Jakartatravel/Adobe Stock; Pillar 2 © Lavizzara/Adobe Stock; Pillar 3 Satoshi Kina/Adobe Stock; Pillar 4 Carol Colman/Pixabay.

4.3. A Social-Environmental Extremes Scenario of Extreme Flooding in Miami, Florida

As illustration of a future scenario in a concise format, we build a scenario for unprecedented flooding in Greater Miami, Florida (see Figure 5). Miami is racially segregated, marked by stark income inequalities and severely exposed to hurricanes and flooding (S. D. Brody et al., 2007; Collins & Grineski, 2017; Wdowinski et al., 2016). It is also characterized by unusual patterns of exposure to floods, making it a stimulating case study for our approach. To integrate the general patterns outlined in Pillar 1, we note that in Miami, coastal areas are severely exposed to flooding but have positive externalities (view, recreation, high-value properties). They are thus mostly inhabited by higher income non-Hispanic white groups (Chakraborty, Collins, Montgomery, & Grineski, 2014). Although these residents are more exposed to flooding, risks are offset by insurance and other mitigating measures (Chakraborty, Collins, Montgomery, & Grineski, 2014; Wakefield, 2019). Inland areas instead have a lower exposure yet a higher vulnerability, making them an exemplary expression of the class-race-vulnerability nexus (Collins & Grineski, 2017). For example, the federal flood insurance policy provides inadequate protection to vulnerable groups, including immigrants and renters (Chakraborty, Collins, Montgomery, & Grineski, 2014). Moreover, six out of 10 residents in Greater Miami suffer from housing unaffordability and low wages (Florida et al., 2019). These groups are also less able to participate in local governance (Grove et al., 2020).

For Pillar 2, we note that regional climate projections point to both heavier precipitation associated with landfalling tropical Hurricanes (NOAA, 2018; Wright et al., 2015) and more frequent high-tide coastal flooding in the future. This makes unprecedented flooding in the Miami area a plausible occurrence on climate timescales. For Pillar 3, we leverage Hurricane Andrew (1992) and Hurricane Irma (2017). Andrew led to widespread damage, following which higher income neighborhoods could redevelop faster than low-income and minority neighborhoods. In the latter areas, black households were the slowest in recovering: home abandonment was particularly high and the Hurricane generally undermined stability and housing value (Zhang & Peacock, 2009). Irma, on the other hand, will be remembered for the significant coastal flooding it occasioned, which damaged a number of affluent coastal developments (Harris, 2017). Its aftermath was

marked by uneven recovery trajectories, with media reporting faster responses in higher income neighborhoods (clearing of debris and restoration of power), environmental racism in siting of debris waste facilities and food insecurity in the most vulnerable communities (Campbell, 2017; Shumow, 2019). As a fourth pillar, we leverage Katrina to examine the political economy of flood-related disasters. Similarly to New Orleans, Miami's economic model is grounded on wetland alteration, rapid suburbanization and large-scale infrastructure projects that increased exposure to flooding and sea-level rise (Blessing et al., 2017; Grove et al., 2020). Although Miami has officially embraced a resilient city approach, this label conceals the same economic growth model that has produced environmental degradation, devalued black areas and created white spaces of growth (Grove et al., 2020), as previously witnessed in New Orleans. In New Orleans, these tensions were not resolved in the aftermath of Katrina, that ended up reinforcing, rather than transforming the preexisting economic model. Local and state government deflected attention from political responsibilities by emphasizing the magnitude and unpredictability of Katrina.

A synergistic application of our four Pillars suggests that unprecedented flooding in Greater Miami could potentially lead to a significant disaster. Despite the unusual patterns of exposure, whereby higher income residents live in areas with a high exposure to floods, we expect to find a significant correlation between race, socio-economic status and vulnerability to an unprecedented flood. Coastal residents will be able to (partly) externalize flood risk and mitigate the impacts of an extreme event. Similarly, we foresee that recovery trajectories will be highly differentiated. Extensive damage, ineffective or nonexistent insurance for lower income residents and an exacerbated affordable housing crisis will constrain recovery of lower income and minority groups. We also expect that an extreme flood in coastal areas may generate gentrification inland, where residents may be unable to redevelop affected properties and might be bought out by higher income residents. This process will be particularly intense if high-income coastal areas experience a level of flood damage or exposure that cannot be offset through insurance and other mitigating measures. We foresee that the government's response will focus on higher income areas and on producing a narrative of unpredictability and unprecedentedness to minimize political accountability. Miami's deeply rooted economic growth model will persist or might even benefit from the disaster, through large developments and real estate projects in flood-damaged areas. Yet, based on Hurricane Katrina, we also expect the consolidation of social movements promoting notions of resilience and disaster risk reduction grounded on overcoming racial and economic inequalities, a process which today is in its infancy (see also Grove et al., 2020). The extent of their ability to trigger change in an economically and racially exclusionary development model will depend on contextual factors that are less predictable.

5. Discussion and Conclusions

In this paper, we developed a new knowledge base to unravel the complexity of the multiscalar societal responses to unprecedented environmental extreme events. The potential of our scenario-based approach was demonstrated by focusing on extreme flood events, and by specifically considering the case of a scenario hindcasting Hurricane Harvey-like flooding in Houston, Texas. While this exercise served to validate our approach, the full potential of Social-Environmental Extremes Scenarios lies in providing plausible scenarios of future responses to unprecedented extremes, as exemplified by the future scenario for unprecedented flooding in Greater Miami.

We note two significant contributions of our approach to advance the understanding of social-environmental extreme events. First, the Social-Environmental Extremes Scenarios approach is highly scalable. The scenarios may take the form of detailed, circumstantial descriptions such as the ones provided for Houston, or be limited to a brief outline of each pillar and of the salient societal responses to future extremes, such as the example given for Miami. At the same time, our approach is flexible, and can be adjusted and applied to a wide range of extreme events, including heatwaves, drought, wildfires, earthquakes, and interconnected social-environmental extremes. We, thus, encourage new research that explores the potential of this approach on specific case studies focusing on a spectrum of social-environmental extremes, as well as the potential of this approach to capture future scenarios of unprecedented events beyond the conventional realm of environmental extremes, such as epidemics or pandemics. Second, our approach transgresses disciplinary boundaries to integrate critical social theories on multiscalar societal responses to social-environmental extremes (Pillar 1) with projections drawn from the event-specific literature (Pillar 2), and multiple

empirical analyses of social-environmental extremes and events of different magnitudes (Pillars 3 and 4), as what is unprecedented in a given place may have been experienced elsewhere. We argue that this rigorous and systematic analysis of different social-environmental extremes provides a unique approach to account for and unravel their complexity. Global change, which is exacerbating extreme event occurrences, makes this effort particularly urgent. In the coming decades, many locations around the world are expected to face social-environmental extreme events of an unprecedented nature (Abatzoglou & Williams, 2016; Gariano & Guzzetti, 2016; Giorgi et al., 2018; Marvel et al., 2019; Murray & Ebi, 2012; Pfahl et al., 2017; Vogel et al., 2019). An understanding of possible societal responses to such extremes is essential to mitigate their adverse socio-economic impacts.

As we show with our approach, central to this effort is the recognition that society cannot be understood as "undifferentiated whole" (Moore, 2017, p. 595). Recognizing and accounting for heterogeneity in society is imperative to unravel the genesis of unprecedented events, accumulation and distribution of risk, and recovery trajectories. It is through intersecting differences—socio-economic, political, ideological—and asymmetrical power relations that societal responses are produced. This has important implications on the way future social-environmental extremes in the Anthropocene are conceptualized. The concept of the Anthropocene has the potential to promote scholarship that examines extremes and social processes relationally and to foster interdisciplinary collaborations. However, as suggested by a growing body of literature (Biermann et al., 2016; Castree et al., 2014; Hulme, 2010; Lidskog & Waterton, 2016), the concept must be approached with caution, recognizing that the "humanity" (Anthropos) of the Anthropocene is not unified and homogenous. Without this understanding, scenarios are unlikely to capture where and why vulnerability is generated and how different societal groups and interest coalesce or are antagonized in human responses to social-environmental extremes.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All data are available in the main text.

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