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Defining Extreme Events: A Cross-Disciplinary Review

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Defining Extreme Events: A Cross-Disciplinary Review

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Key Points:
- What constitutes an extreme event varies by study and discipline; thus we must be explicit in how we define extreme events
- Extreme events are often conflated with their impacts, but this will inhibit future recognition of resilience
- Bridging across disciplinary differences in communication and definitions is critical for holistic management of extreme events

Supporting Information:
- Supporting Information S1
- Supporting Information S2

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Abstract Extreme events are of interest worldwide given their potential for substantial impacts on social, ecological, and technical systems. Many climate-related extreme events are increasing in frequency and/or magnitude due to anthropogenic climate change, and there is increased potential for impacts due to the location of urbanization and the expansion of urban centers and infrastructures. Many disciplines are engaged in research and management of these events. However, a lack of coherence exists in what constitutes and defines an extreme event across these fields, which impedes our ability to holistically understand and manage these events. Here, we review 10 years of academic literature and use text analysis to elucidate how six major disciplines—climatology, earth sciences, ecology, engineering, hydrology, and social sciences—define and communicate extreme events. Our results highlight critical disciplinary differences in the language used to communicate extreme events. Additionally, we found a wide range in definitions and thresholds, with more than half of examined papers not providing an explicit definition, and disagreement over whether impacts are included in the definition. We urge distinction between extreme events and their impacts, so that we can better assess when responses to extreme events have actually enhanced resilience. Additionally, we suggest that all researchers and managers of extreme events be more explicit in their definition of such events as well as be more cognizant of how they are communicating extreme events. We believe clearer and more consistent definitions and communication can support transdisciplinary understanding and management of extreme events.

Plain Language Summary Extreme events, such as heat waves, widespread flooding, or very strong storms, are of interest to scientists and managers because of their potential to cause extensive damage and impacts on people, infrastructure, and nature. With climate change causing more of these events to happen, it is important that we understand how or when they might occur, and how to better respond to them to prevent disastrous impacts. For these reasons, researchers from many different subject areas study extreme events. However, we show that researchers from different backgrounds may use very different words to communicate about these events and different ways of deciding what makes an extreme event "extreme." In order for researchers, managers, and planners to help everyone better prepare for and respond to extreme events, we encourage all researchers to improve how they explain why they are studying a particular event and make greater effort to understand the work that colleagues in other subject areas are doing and how that may affect our own research and practice.

1. Introduction

Natural hazards have affected communities since ancient times. More recently, we are experiencing an increase in disasters (Figure 1; United Nations Office for Disaster Risk Reduction [UNISDR], 2013), which are hazards or events that generate impacts on our social, ecological, and/or technical systems. While the

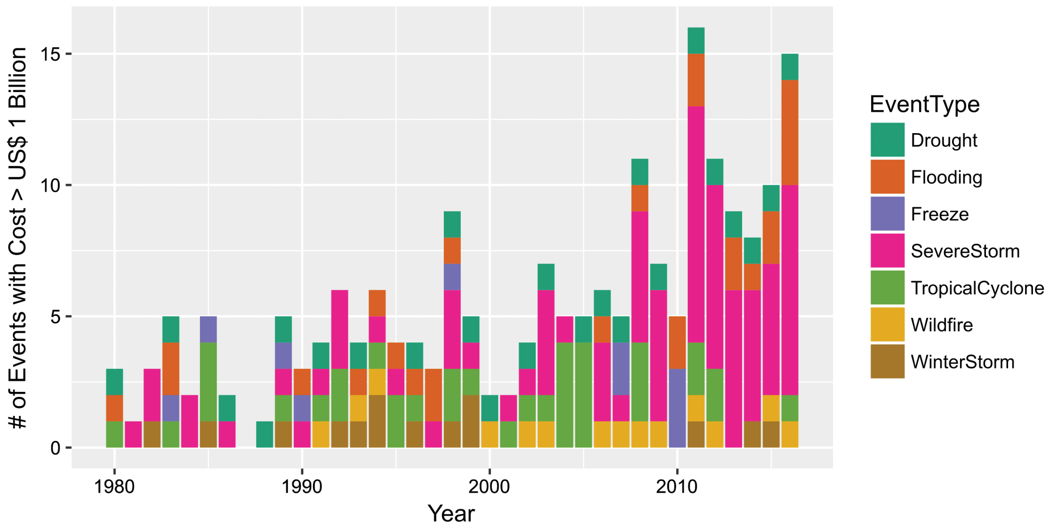

Figure 1. Yearly occurrence of extreme events in the United States (as of 7 July 2017) whose impacts cost greater than 1 billion U.S. dollars (CPI-adjusted). Data were obtained from the National Centers for Environmental Information (https://www.ncdc.noaa.gov/billions).

number of deaths has not been increasing, there have been observed increases in the total number of people affected and monetary damages (Chang et al., 2012; UNISDR, 2013). This increase in disasters can be partly explained by considering the expansion of cities and suburban areas into hazard-prone zones, and the subsequent increased exposure of people and infrastructure (Bouwer, 2010; Chang & Franczyk, 2008; Intergovernmental Panel on Climate Change [IPCC], 2012). Globally, more than 50% of the world's population now lives in cities, with overall urban population and rates of increase varying by region (United Nations Department of Economic and Social Affairs, 2014). As of 2010, 39% of the U.S. population lives in coastal shoreline counties (National Ocean Service, 2013) and thus is exposed to direct impacts from coastal storms, storm surges, and sea-level rise (Neumann et al., 2015). Cities are also more vulnerable to extreme heatwaves due to the exacerbation of impacts from the urban heat island and air pollution (Méndez-Lázaro et al., 2015, 2017). With higher population density and potentially fragile infrastructure, cities are also often more vulnerable than their surrounding areas to earthquakes (Pelling, 2003), cyclones, or coastal flooding (De Sherbinin et al., 2007). Taken together, these studies suggest that cities are a critical locus of exposure, risk, and vulnerability to extreme events. Some of these exposures have been mitigated by improved engineering solutions and early forecast technology, helping to reduce loss of lives and some financial and infrastructural impacts (Chang et al., 2012; Fuchs et al., 2011; Wilby & Keenan, 2012). Cities also are at the forefront of efforts to build resilience to climate change and other threats (Rosenzweig et al., 2010). Resilience has many definitions (Meerow et al., 2016) and a complex relationship to vulnerability (Gallopín, 2006), and in the interest of clarity we specify this definition for this paper: the ability of a social-ecological-technical system (SETS) to withstand shocks and perturbations without losing its structure, function, feedbacks, and identity, and even to transform when such change is essential to maintenance of the SETS (The Royal Society, 2014).

Change in exposure and vulnerability is compounded by changes in frequency and magnitude of certain hazards due to climate change. Attribution of events to climate change is still an emerging field, particularly when considering individual events; however, there is strong evidence of the links between increasing trends of hydrometeorological and climatological hazards and climate change (National Academies of Sciences, Engineering, and Medicine [NASEM], 2016; The Royal Society, 2014). A global increase in annual maximum daily precipitation has been documented (Westra et al., 2012) as well as an increase in global temperature since 1861 (Folland et al., 2001). The IPCC's global report on extreme weather events (IPCC, 2012) states that it is very likely that there has been an increase in the number of warm days and warm nights. Extreme heat events are expected to increase in frequency, intensity, and duration throughout the 21st century (Meehl & Tebaldi, 2004). Modeling results indicate an acceleration of the hydrologic cycle in a warmer climate with potentially large impacts on the frequency of extreme events (Huntington, 2006). Many regions are projected to experience an increasing number of days of heavy precipitation, although

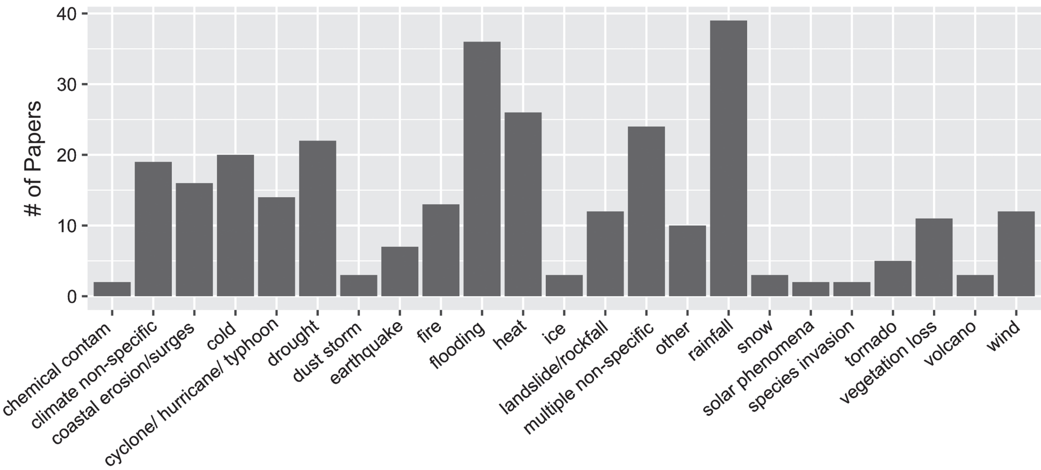

Figure 2. The type of extreme event studied. 'Other' includes event types that were examined in only one paper in our review.

this varies regionally (IPCC, 2012; Kunkel, 2003; Walsh et al., 2014). More intense cyclones with stronger storms are also projected to increase (Knutson et al., 2010; Webster et al., 2005).

The capacity of interacting social, ecological, and technical infrastructure components of complex systems to buffer and adapt to various climate-driven changes is a significant issue facing decision-makers. Therefore, we use a recently developed SETS framework (Grabowski et al., 2017; Grimm et al., 2015; McPhearson et al., 2016a, 2016b) for considering definitions of extreme events in multiple types of systems. There is a need to understand these interdependencies and how various extreme events will intersect to create risk and vulnerability in complex and dynamic human-dominated systems. Our understanding of these events and potential vulnerabilities affects our ability to enhance resilience to these events or plan for recovery.

However, this understanding is hindered by a lack of coherence in what constitutes and defines extreme events across the many disciplines, both in terms of their causes or attribution and their impacts. This is not surprising because these many disciplines—social sciences, engineering, ecology, hydrology, climatology, and earth sciences—emphasize different aspects of extreme events and have different ultimate motivations. Yet, bringing clarity and coherence to the definition of and communication related to extreme events will benefit all of these perspectives, by (1) widening the nature of our fundamental understanding, (2) enhancing our ability to holistically understand and manage extreme events, and (3) providing more useful and actionable information to practitioners, that is, those who need to act on this knowledge.

1.1. Background of Research on Extreme Events across Disciplines

1.1.1. Hazards in Earth Science

A hazard in the earth sciences is a natural event that has the potential for a significant negative impact on humans, infrastructure, or the environment. Geophysical, atmospheric, and hydrologic extreme events are some of the primary hazards studied in earth science (Cutter, 1993; Fowler & Hennessy, 1995; Gill & Malamud, 2014; Magilligan, 1992; Mason et al., 2004; White, 1974). Scientists in this field have focused on mapping, characterizing, and modeling these hazards so that they can understand what factors influence the occurrence and magnitude of a particular hazard (e.g., Douglas et al., 2000; Garcin et al., 2008; Guzzetti et al., 1999; Kunkel, 2003; Peng & Wang, 2015). Using hazard assessment, engineers can then manage risk associated with these hazards, and planners and managers can plan for reducing their potential impacts.

Given changing patterns of weather-related hazards due to climate change and increasing exposure due to the location of buildings and infrastructures (Forzieri et al., 2017; Visser et al., 2014), characterization of extreme events is increasingly motivated by physical and socioeconomic vulnerability to the impacts of such events (Kharin et al., 2007; Méndez-Lázaro et al., 2016; Weisse et al., 2014). In addition, there has been increased focus on the dynamics of compound events; that is, events with multiple simultaneous hazards that may not individually be considered extreme but that, together, have potential for greater overall impacts (IPCC, 2012; Leonard et al., 2014). Examples include extreme flooding due to a combination of

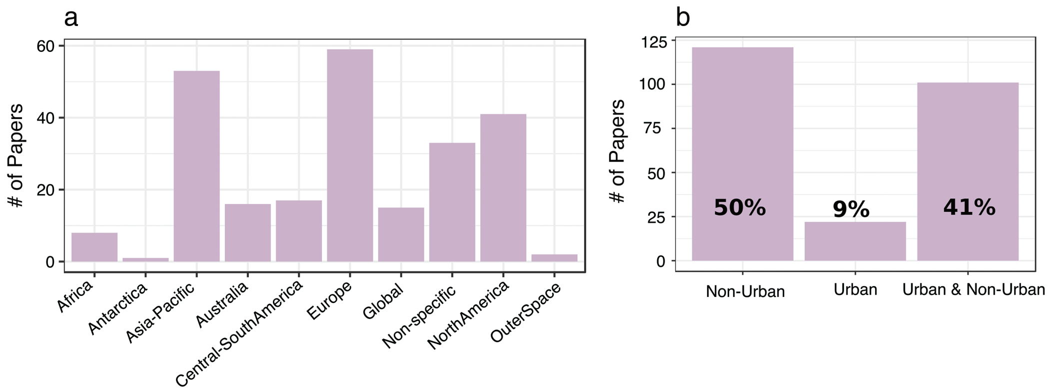

Figure 3. The setting for each paper evaluated, where (a) indicates the continental region in which the study occurred and (b) indicates whether the study area was urban or nonurban.

coastal storm surges and fluvial or pluvial flooding (Moftakhari et al., 2017; Wahl et al., 2015) or concurrent droughts and heatwaves, which may generate extreme impacts when combined (Mazdiyasni & AghaKouchak, 2015). Compound extreme events are of particular interest to the modeling community, given the challenge of accurately and simultaneously predicting multiple hazards (Leonard et al., 2014).

1.1.2. Ecological Disturbance

Ecologists often consider extreme events as disturbances. The concept of disturbance in ecology has a long history of theoretical development, with disagreement over the role of disturbance in enhancing or inhibiting ecological structure and function (Connell, 1978; Grime, 1973; Hutchinson, 1961; Pickett et al., 1989). For example, the intermediate disturbance hypothesis asserts that biological diversity is highest at intermediate intensities or frequencies of disturbance (Connell, 1978), but often other interacting factors beyond disturbance explain diversity (Fox, 2013). Understanding if disturbance is integral or external to a system often requires an integration of hydroclimatic drivers and biotic adaptations. In stream ecology, theoretical developments of the role of disturbance (Resh et al., 1988), such as the natural flow regime (Poff et al., 1997), helped ecologists identify the importance of seasonal variability in maintaining ecosystem viability. Disturbance events that operate on short time scales (pulses) and those that represent longer-term stressors (presses) integrate spatiotemporal scales and drive directions and magnitudes of change in ecological systems (Grimm et al., 2017; Grimm & Fisher, 1989). Press and pulse events are seen as important drivers of social-ecological systems as well, with their impacts on ecological structure and function feeding back to the social system through changes in ecosystem services (Collins et al., 2011).

Disturbance itself is a process, whereby an event leads to impact and reorganization or recovery (Grimm et al., 2017; Peters et al., 2011). The concept of disturbance is also linked to the concepts of ecological resistance, resilience, and stability (Donohue et al., 2016; Folke et al., 2004; Ives & Carpenter, 2007; Rockström et al., 2009). The context of disturbance varies throughout the discipline of ecology, largely because the intensity, magnitude, and duration of any given disturbance all vary across space and time, as well as with antecedent conditions (Resh et al., 1988). Differences in the scale (from microbial to global) of disturbance events relative to the disturbance impacts in SETS influence both response and recovery (Grimm et al., 2017).

1.1.3. Engineering Approaches

In the context of engineering design, extreme events largely appear in the selection of design standards that are typically based on specified return periods, such as 100 or 1000 years (e.g., AghaKouchak et al., 2014). In any given year, the probability of having an event with T year return period is $1/T$ and the return level is the possible magnitude of that event. The probability and return period of events are analyzed using frequency analysis of long-term event data; for example, discharge records. The most common approach is based on annual maxima, where the largest event from each year in the record is selected, and statistical distributions are applied to estimate the probability of occurrence of events of various magnitudes (Lang et al., 1999; Stedinger et al., 1993). Given the dearth of data on extreme events in our records, the challenge lies in choosing appropriate statistical distributions that best capture the tail or most extreme values in these datasets (Stedinger et al., 1993). Partial duration series, also known as peaks-over-threshold analyses, are also used, which evaluate all events over a certain magnitude threshold. It generally produces more accurate frequency distributions, but can be more challenging to employ given decisions about appropriate thresholds (Bezak et al., 2014; Lang et al., 1999).

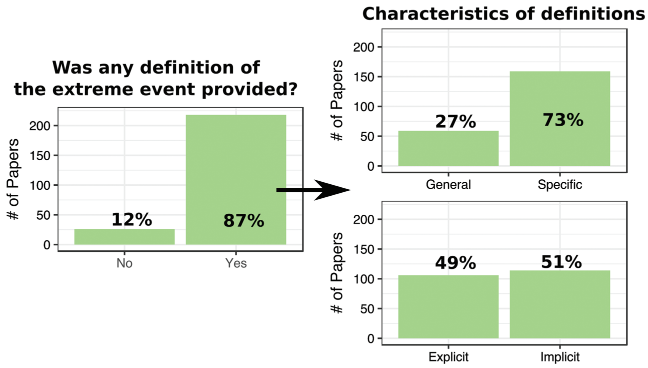

Figure 4. Characteristics of how extreme events were defined in the reviewed papers. 'Specific' indicates definitions which were specific to a particular event type, whereas 'general' definitions are more broadly applicable. 'Explicit' definitions were definitions that were explicitly stated in the study, whereas 'implicit' definitions were implied from other information in the paper.

Standard practice in engineering is to implicitly set an acceptable level of risk through the requirements, so that the infrastructure could be able to remain functional up to a particular return period (Hashimoto et al., 1982; Salvadori et al., 2011; Wheater, 2006). These concepts are useful for design of the structures that are intended to face natural and environmental loads, such as stream discharge or rainfall (Rootzén & Katz, 2013). Different engineering standards based on various criteria, including financial and construction restrictions, have been designated (Barber et al., 2000). For example, a 1000-year return flood is a common criterion in the design of large dams (Rootzén & Katz, 2013; Salvadori et al., 2011). Here, the standards indicate that the dam should be able to maintain operations up to a flood with a 1 of 1000 per year recurrence probability (Salvadori et al., 2011). However, in some cases the expected lifetime of an engineering system is less than the associated design return period, such as a wastewater treatment plant with a project life span of ~30 years that is designed to function under natural loads with 50- or 100-year return periods (Read & Vogel, 2015; Roostaei & Zhang, 2017).

This return period-based methodology strongly depends on the assumption of a stationary climate, which means no change over time in the probability of occurrence of extreme events (Cheng et al., 2014; Milly et al., 2008; Read & Vogel, 2015). Owing to strong evidence of a changing frequency of extreme events (Milly et al., 2008), engineers are beginning to consider how to incorporate nonstationarity in their frequency analysis and design (Katz, 2013; Katz et al., 2002; Read & Vogel, 2015) and are developing a resilience-based approach to adaptive management (Park et al., 2013).

1.1.4. Social Science Perspectives on Disaster Risk Reduction (DRR)

Hazard and disaster studies within the social sciences examine the complex relationship between humans and environment, focusing on underlying social conditions that influence and/or are influenced by extreme events. The concept of "disasters" is used to qualify significant impacts and the extremity of a hazard post-event (e.g., loss of life, damage to economy and environment). Disasters are framed by the vulnerability of SETS and by the ability to respond to the hazard that has caused a type of disturbance or condition change. The quality of response to the hazard has been studied in relationship to (but not limited to) social memory and social capital (Folke et al., 2005), formal governance institutions (Zaidi & Pelling, 2015), and local level development trajectories and policy (Gibson et al., 2016).

The quality of response reveals capacities of social systems to respond to underlying vulnerabilities and uncertainty related to hazards. The Hyogo Framework for Action 2005–2015 and subsequent Sendai Framework for DRR 2015–2030 were adopted on the international scale to reduce disaster risk by putting frameworks in place to improve quality of response to such events. DRR strategies were constructed from a development discourse with the intention of sustaining long-term responses to minimize socioeconomic vulnerability and exposure to hazards. Working within the sustainable development framework, the DRR discourse has been used predominantly by the international community for application in developing countries or countries deemed to have high socioeconomic vulnerability and high exposure to hazard. This approach has been supported by development and DRR literature that has studied "natural" hazards to be a set of socially constructed relationships between humans and environment, requiring strategies that frame risk within particular historical, social, political, environmental, and economic contexts (Wisner et al., 2004).

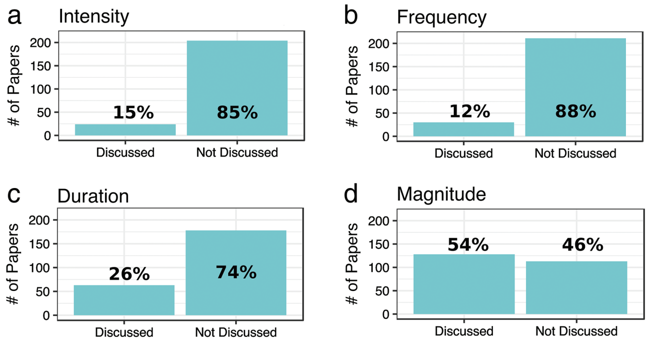

Figure 5. Summary of what characteristics related to the extreme events were discussed in the reviewed papers, including (a) intensity, (b) frequency, (c) duration, and (d) magnitude.

Questions have emerged within the social science literature concerning the compatibility of DRR and climate change adaptation (CCA) strategies, which has implications for management of and response to hazards (Thomalla et al., 2006). As certain types of extreme events increase in frequency (IPCC, 2012), the question of which strategies would best serve to deal with impacts differs between the two approaches. Most temporal aspects of DRR approaches to extreme events use past and current impacts of events to assess response, while CCA primarily focuses on present and future impacts of events (Mercer, 2010). Concern lies with whether CCA strategies might be redundant to already existing DRR strategies in the face of extreme events (Birkmann & von Teichman, 2010).

1.2. Problem Statement and Objectives

Commensurate definitions for extreme events are critical for decision making. While it might be fine for extreme events to take on different definitions and meanings across various disciplines, problems are likely to arise when a particular discipline does not have clear meaning for the term. Additionally, extreme event definitions are of value to different audiences for different reasons. Academics need the term to understand change and assess impacts, helping to develop resilience concepts. Infrastructure managers need the term to decide how to deploy physical assets, including adaptation strategies, to understand the context for the events they must face. Private companies, such as insurance firms, need the term to describe risk to assets. Different audiences require different information to manage the potential events and their impacts. Incommensurate definitions threaten to create misaligned information that could lead to challenges in decision making. For example, a public health agency that is tasked with protecting vulnerable groups during heat waves may be conflicted on how to issue warnings if studies use different definitions of extreme heat that consider different measures of intensity and duration. Consistent definitions of the term are critical, both to benchmark the significance of events and to decide what should be done to mitigate impacts.

Thus, in this paper we evaluate the currently understood definitions of extreme events within different disciplines through a literature content analysis. We then propose a common framework for defining extreme events that can be used across social, ecological-biophysical, and technical-infrastructural disciplines.

2. Data and Methods

We performed a review of academic literature in May 2016 using the Web of Science. We chose search terms to specifically capture papers from a variety of disciplines and focused on papers published from May 2006 to May 2016. The final search was "TITLE: (disturbance OR extreme event OR severe weather OR hazard OR disaster) AND TOPIC: (climate OR weather OR meteorological OR hydrological) AND TOPIC: (defining OR definition OR define) from mid-2006 to 2016." This search yielded 244 papers which were included in the review along with 12 patents/datasets that were excluded and 56 papers that were inaccessible.

We grouped papers manually into disciplines based on the journal, paper title, and paper scope. The disciplines that we used included climatology ($n = 68$), earth science ($n = 32$), ecology ($n = 60$), engineering ($n = 19$), hydrology ($n = 14$), and social science ($n = 51$). We originally included economics as a discipline; only six papers fell into this category, so they were lumped into the social science category.

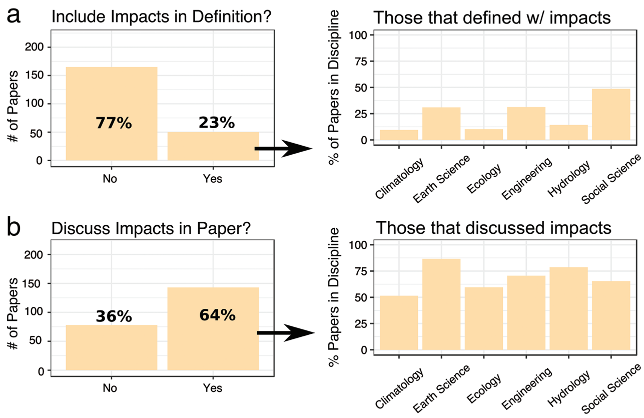

Figure 6. Management of impacts in the reviewed papers, where (a) shows how many papers explicitly included impacts as part of their definition of extreme events, and from which disciplines those papers came and (b) shows how many papers discussed impacts in the course of the paper, and from which disciplines those papers came.

For each paper, we extracted relevant information on the context and definition of extreme events. These characteristics included the setting, hazard type, their definition of extreme events, and characteristics of the extreme event (duration, magnitude, intensity, frequency, impact/losses). We summarized these characteristics using R statistical software. We also used word analysis to evaluate the extracted extreme event definitions (McPhillips & Herndon, 2017). This analysis was performed using R packages "tm" and "SnowballC." Briefly, we imported the text, cleaned it up by removing common words (e.g., "the") and symbols, stemmed all words to their root (e.g., "change" or "changing" become "chang") and calculated their frequency. We also used text analysis to evaluate the language of the papers themselves, using the same methods described above after extracting the text and removing the reference sections. We then analyzed word frequency across the disciplines and used cluster analysis to explore the similarity between language used in the papers from each discipline.

3. Results

A growing interest in extreme weather events is reflected in the fact that climatology was the discipline with the greatest number of papers, and the most frequently examined types of events were weather-related. The top four events were rainfall, flooding, heat, and drought (Figure 2). The geographic locations of the studies encompassed all continents, with Europe and Asia-Pacific having the greatest representation (Figure 3a). Less than 10% of studies were focused in urban areas (Figure 3b), which is surprising given the potential for substantial impacts in these areas with their high concentrations of humans and infrastructure.

A total of 87% of examined papers included some definition of extreme events (Figure 4). Among these papers, about half explicitly stated their definition of the extreme event of interest, while for the other half their connotation was implied. As Stephenson (2008) notes, "extreme events are generally easy to recognize but difficult to define." A total of 27% of all papers with some sort of definition had a definition considered generalizable across multiple types of events (e.g., "high-impact, hard-to-predict phenomenon that is beyond our normal (i.e., Gaussian bell curve) expectations"; Sura, 2011). The remainder had a definition specific to the event being examined (e.g., Standardized Precipitation Index less than −1; Zhang et al., 2014).

When we examined how extreme events were characterized, intensity, frequency, and duration were discussed in less than a quarter of papers reviewed (Figures 5a–5c). Much more commonly discussed (54% of papers) was magnitude (Figure 5d). The way magnitude was used varied, including both absolute numeric thresholds (e.g., 10,000 ha burned by wildfire or 100 °F temperature) and statistical thresholds (e.g., 90th percentile). Specified statistical thresholds generally ranged from 90th to 99th percentile, with 99th percentile and 100 year return period being most common.

Inclusion of impacts was the other key characteristic examined. A total of 23% of papers explicitly included impacts in their definition of extreme events. Of these, social science papers had the highest fraction that included impacts in their extreme event definition (Figure 6a). A total of 65% of all papers discussed impacts as a motivator for studying and understanding extreme events. These papers were more evenly distributed, with climatology still being lowest (Figure 6b).

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	Climatology	Earth Science	Ecology	Engineering	Hydrology	Social Science
1	**Event**	**Hazard**	Disturb	Surg	**Flood**	**Disast**
2	**Extrem**	**Area**	Forest	Wind	**Event**	**Risk**
3	Precipit	Wave	Fire	**Event**	**Risk**	**Hazard**
4	**Model**	Coastal	Speci	Storm	**Disast**	Resili
5	Temperatur	**Model**	**Area**	**Hazard**	**Model**	**Vulner**
6	Region	Factor	**Chang**	**Extrem**	**Area**	**Chang**
7	**Climat**	High	Soil	**Vulner**	**Hazard**	**Event**
8	Day	Rock	**Studi**	**Model**	Water	Communiti
9	**Data**	**Data**	Tree	**Flood**	River	**Climat**
10	Observ	Level	**Climat**	**Data**	Year	**Studi**

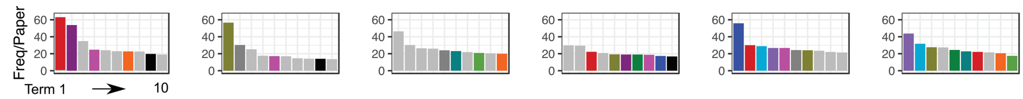

Figure 7. Table of top 10 most frequently occurring word roots in the papers reviewed from each discipline. Bolded words occur in more than one column; each is represented by a different color to aid in visualizing similarities across the various disciplines. The histograms represent the frequency of occurrence of these top 10 words, where the frequency is normalized by the total number of papers examined in that discipline.

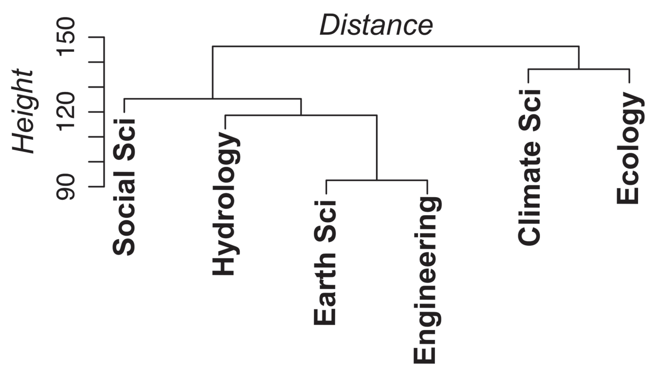

Figure 8. Cluster dendrogram visualizing similarity in language used in reviewed studies within each discipline. Distances were computed using Ward's minimum variance method.

When we evaluated the specific language used to discuss extreme events, the most frequent word roots occurring in the extracted definitions were related to event types (precipit, flood, temperatur), event magnitude (high, percentile, exceed, threshold, extrem), event impact (impact, damage, valu), and occurrence (event, occur, caus). Looking across all language used in the papers—not just the specific extreme event definitions—we identified differences in language among the disciplines, with top words from all papers in each discipline varying substantially (Figure 7). For example, disaster (and its variants) is a common word in social science and hydrology, but is not common in the other disciplines examined. Cluster analysis revealed the relationships between these different bodies of language, showing that ecology and climatology clustered separately from the other more risk-focused disciplines (social science, hydrology, earth science, and engineering; Figure 8).

4. Discussion

4.1. Exploring Variability in Definitions of Extreme Events and Impacts

This analysis elucidates the variability in ways that extreme events are defined across six major disciplines that examine them. It is concerning that 12% of all papers examined provided no definition whatsoever and 51% did not directly state what their definition or connotation was. Even within those with some definition, which elements were mentioned (e.g., magnitude, duration, frequency) was highly variable, as was the type of threshold used (e.g., absolute, statistical). Without a clear understanding of how an event was chosen or why it was examined, advancing our knowledge of these events and their impacts is much more difficult.

The disciplines examined varied in both characteristics of definitions and elements of language used. A key language difference was in the types of words used to describe extreme events and impacts. While sometimes "extreme event" was explicitly used, often similar terms were used that have slightly different connotations. In ecology, "disturbance" has historically been used to describe events of varying magnitude, though we did find the term "extreme event" being used more often in the more recent papers examined. In earth science as well as hydrology, engineering, and social science, "hazard" referred to events of varying magnitude, while use of "disaster" (most common in social sciences) specifically referred to events with substantial impacts. With these variations in language, it is again critical to be as explicit as possible in how an event is defined or characterized.

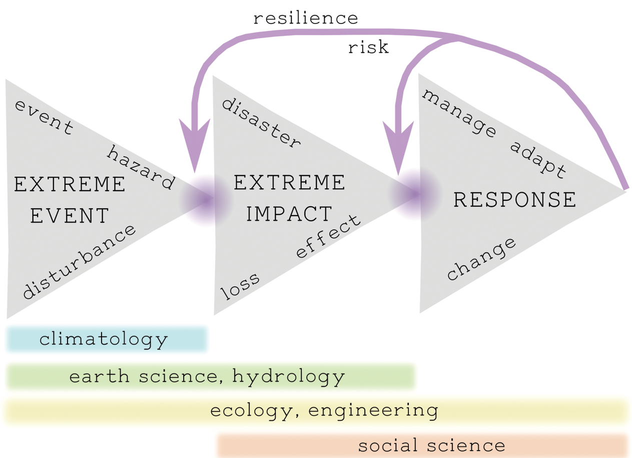

Figure 9. Transdisciplinary framework for conceptualizing extreme events, their impacts, and the response to them, including a feedback from response choices to the nexus between event and impacts, and between impacts and subsequent responses. Some of the different terms used across the various disciplines to describe these periods are indicated, and the general niches of the examined disciplines are highlighted to indicate areas of overlap and difference in focus.

One of the most striking sources of variation in extreme event definitions was whether or not impacts were included. Potential or actual impacts were also mentioned as a motivator of many of the examined papers. Sometimes impacts implicitly informed choice of magnitude thresholds in extreme event definitions, such as defining a threshold for a heat wave based on specific potential detrimental health impacts; again, being as explicit as possible in what motivates the definition is critical (Otto et al., 2015). With regard to explicitly including observed impacts (e.g., an event where loss of life occurs) in the definition, we find this concerning. Our motivation in studying extreme events, similar to that of many other researchers, is to lessen negative impacts on SETS. However, if we are successful in managing and redesigning our systems such that they are resilient to a particular extreme event, how would we recognize that success if we were defining the event based on impacts? For this reason, we urge that definitions of the extreme events separate events and impacts whenever possible.

4.2. Complexities in Discerning Events from Impacts

Extreme events and impacts have an intimate relationship mediated by system vulnerabilities and response capacities. Uncertainty of risk and varying predictive power of hazard forecast modeling create an elusiveness of the extreme event, in which impacts cannot be fully assessed. Disaster studies have conceived of impact as regulating the "extremeness" of the natural hazard (event), bringing attention to the thresholds of a system (e.g., determine which situations we may define as "disaster"). Magnitudes and thresholds are bounded by the social and cultural context of a society (Wisner et al., 2004) that accumulates over time and space to affect the distribution of risk and social and environmental change (Manuel-Navarrete & Pelling, 2015). Because the social environment is created through human action and decision-making, it underlies the adaptive capacity of a system and is a key characteristic contributing to resilience (Solecki et al., 2011). Determining a system's resilience is part of a larger family of elements within risk, such as vulnerability, disaster, and culture (Gallopín, 2006; Wisner et al., 2004), complicating attempts to separate the event from the impact. The social science literature of this review has focused primarily on the event and impact together to examine a system's ability to respond, and prevailing resilience. Separating extreme event from impact becomes a gray area when considering expansive types of change that may need to take place, such as transformational adaptation, which includes technological responses but also anticipatory actions and larger-scale behavioral change (Kates et al., 2012) that are more challenging to isolate.

The impact of an extreme event also depends on a region's SETS, which are dependent on the development history of a given region. Previous policy decisions regarding land use, zoning, and infrastructure all affect the level of exposure to hazards, susceptibility, and the adaptive capacity of the system to cope with the impacts caused by extreme events (Cho & Chang, 2017). Take Hurricane Katrina for example: had the levees not been constructed along the lower Mississippi River nor the shipping canals built, extreme impacts of the floods could have been avoided, saving the hundreds and thousands of residents who used to live on the floodplain. Looking forward, if wetlands or floodplain areas are restored, flood risk is projected to decline

(Ahilan et al., 2016). Improving ecological resilience could thereby enhance social resilience. Regardless, it is critical to acknowledge these many intertwined factors, feedbacks, and legacies as we work to better understand and respond to extreme events and their impacts.

4.3. Implications for Management of Extreme Events and Impacts

Management of extreme events and impacts varies due to the unpredictability of these events and their unexpected impacts. As literature across the disciplines has addressed, climate change is expected to alter the frequency and duration of certain hazard events, causing academics and managers alike to question current thresholds and magnitudes that may define an extreme event. While the natural sciences and social sciences will empirically focus on different aspects of hazards (i.e., quantitative based studies isolating the natural event itself vs. qualitative studies of socioeconomic contexts underlying disaster), the management realm faces a complex situation in which decision-makers need to apply ideas from consulting agencies, experts, and academics while simultaneously dealing with societal and economic contexts. Attitudes and judgment influence how the event and impact are to be encapsulated and managed. Discrepancies in interpretation between individuals, institutions, and groups is commonplace (Mitchell, 2006). Partnerships have been suggested to mediate conflicting and contradicting paradigms that advance new strategies for hazard management (Mitchell, 2006). As recognized by United Nations Sustainable Development Goals 2030, "public-community partnerships" or "civil society partnership" (as opposed to "public-private partnerships") have resulted in greater engagement with participating institutions and with underrepresented minority communities, which are often disproportionately affected by extreme events.

Urban systems may be ideal locations in which to bridge these interdisciplinary gaps. This analysis revealed a lack of focus on urban areas in extreme event research. Yet, these are the areas where impacts continue to increase, as evidenced by recent events (Hurricane Harvey in Houston, TX, Hurricane María in Puerto Rico, and Hurricane Irma in the Caribbean, Florida Keys, and Peninsular Florida). In September 2017, Puerto Rico (PR) experienced one of the most catastrophic hurricane seasons in recent history. In a matter of 2 weeks, the island was impacted by two major hurricanes, Irma (category 5) and María (category 4). These extreme events cumulatively pummeled the island's power, water, communications, and transportation infrastructure. This necessitated a response that included interdisciplinary cooperation, demonstrating how the extreme event itself may catalyze or facilitate successful transdisciplinary partnerships among researchers and stakeholders. Key to such partnerships, however, is effective communication about extreme events. As more cities push to develop strategies to manage extreme events and to enhance resilience to them, engaging stakeholders or practitioners in partnerships with transdisciplinary researchers will generate more actionable materials and knowledge (Podesta et al., 2013).

A common challenge in interdisciplinary collaborations is effective communication or common language (Pennington et al., 2013), and our results highlight the importance of consistently defining extreme events for disciplinary and especially transdisciplinary research and decision-making. While incommensurate definitions (or no definition at all) across disciplinary literatures abound, these explorations of the impacts of extreme events provide valuable insights towards a stronger understanding of the effects of climate change. Yet as research progresses and becomes increasingly embedded in decision-making (Adger et al., 2003; Ahern et al., 2014; McDaniels et al., 2008; NYC, 2017; Schipper et al., 2016), we anticipate a need for more consistent definitions of extreme events across hazards. Incommensurate definitions may create barriers for the use of actionable information, a large number of context-specific recommendations, or misinterpretation—leading to skepticism by decision-makers or the general public about the possible outcomes of events. While challenges await in establishing consistent definitions within disciplines, even greater challenges may exist in interdisciplinary research, given large differences in definitions of extreme events and the even larger gap to reconcile and make sense of these differences. Interdisciplinary efforts would benefit greatly from focused efforts early in projects that seek to establish understandings of how the term is used and how that affects the design process. Patience, humility, and flexibility can go a long way in helping participants respectfully overcome differences. Simple conceptual models, diagrams, development of common vocabularies, and real-time assessment of communication issues can also aid in converging towards a common goal (Bracken & Oughton, 2006; Bruce et al., 2004; Hinrichs et al., 2017; Pennington et al., 2013; Podesta et al., 2013). In this way, we can create fruitful interdisciplinary partnerships that will drive the highly creative thinking behind the truly transformative solutions needed to address problems (Pennington et al., 2013) like assessment and management of extreme events.

5. Conclusions

In our review of literature addressing extreme events from a wide range of disciplines, we found great variability in the nature of definitions and language used to discuss extreme events. Less than half of examined papers provided an explicit definition of what they considered to be an extreme event. Among those that specified a threshold of "extremeness," various numeric and statistical thresholds were used, with 99th percentile or 100 year return period being the most commonly identified. A total of 23% of papers included impacts in their definition of an extreme event, with papers from social sciences comprising the greatest proportion. There were clear differences in terminology used across the various disciplines; for example, disturbance is a popular way of conveying major reorganizing events in ecology while disaster is a similar term preferred in social sciences literature. Additionally, only 50% of papers addressed extreme events in urban areas, despite the fact that these areas are hotspots of exposure and vulnerability. In an attempt to bridge these differences in characterization and management of extreme events, we provide the following key findings to guide future interdisciplinary scholarship of extreme events and transdisciplinary research to build resilience.

We must recognize where our own efforts related to the study and management of extreme events fall relative to other disciplines and work to communicate across these boundaries. This review highlighted niches occupied by various disciplines along the cycle of extreme events, impacts and response along with corresponding differences in language used to discuss these (Figure 9). There are also opportunities for feedbacks in the extreme event process (Figure 9), which may lead our work in one domain to influence that in another part of the process. To better understand and manage these events in a holistic, transdisciplinary manner, it is critical that we acknowledge and work to better communicate across disciplinary boundaries.

Definitions of extreme events should not be conflated with their impacts or effects. Conflating the events with impacts could jeopardize our ability to assess resilience to extreme events. Where disciplines diverge in their definitions of extreme events and impacts, we find potentially fruitful areas for transdisciplinary consideration in urban systems, or more generally in SETS.

Thresholds used to define an extreme event can be based on probabilities of occurrence or on the point where they have potential consequences or impacts. As noted above, an extreme event should not be defined based on what impacts actually occurred; however, the consideration of the potential for impacts based on vulnerabilities to various components of the SETS is a valid means of defining an extreme event. Traditional approaches of statistical thresholds are also valid (e.g., 99th percentile or 100 year return period), although we urge increasing consideration of nonstationarity in event probability due to climate change in the decisions regarding these thresholds, particularly related to design and engineering applications.

We all should be more explicit in defining what we mean by an extreme event or an extreme impact. We do not feel that we can present a single unifying threshold for defining extreme events as the appropriate threshold could vary depending on event type, system thresholds, geographical, or social context, researcher or manager goals, or other factors. In endorsing variable means of defining extreme events, it becomes critical that we all are very clear and deliberate in articulating our definition. In order to make these definitions most useful, we urge that they include event type, potentially affected SETS, the threshold that is being used to characterize the event as extreme, and rationale for the chosen threshold.

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