More than Magnitude: towards a multidimensional understanding of unprecedented weather to better support disaster management

More than Magnitude: Towards a multidimensional understanding of unprecedented weather to better support disaster management

Dorothy Heinrich [a,c], Elisabeth Stephens [a,c], Erin Coughlan de Perez [b,c]

[a] *Department of Meteorology, University of Reading, Reading, UK*
[b] *Friedman School of Nutrition Science and Policy, Tufts University, Boston, USA*
[c] *Red Cross Red Crescent Climate Centre, the Hague, Netherlands*

A B S T R A C T

The 1900 Galveston Texas Hurricane, the 2021 Pacific Northwest heatwave, and the 2023 Tropical Cyclone Freddy were all events that were unprecedented in diverse ways and had severe humanitarian impacts. Understanding past and future risk of unprecedented weather is an emerging question across climate science disciplines but use of this research by the humanitarian sector has been limited. This cross-disciplinary paper is an effort by climate scientists and humanitarian practitioners to address this gap. For it, we combined narrative and scoping literature reviews with structured practitioner engagement to develop a working definition and typology of unprecedented weather through a disaster management lens. We qualitatively coded over 400 peer-reviewed articles to highlight the current state of research on unprecedented weather, and then discussed these findings in a workshop with 48 humanitarian practitioners. Our results show that, while analyses of past and future unprecedented weather often focus on the magnitude of such events, extreme weather can be unprecedented in many other dimensions, all which have significant implications for early warning, anticipatory action, and disaster response planning. We conclude with a call for more imagination and diversity in research on extreme weather risks, and for closer collaboration between climate scientists and disaster managers to design and answer questions that matter for humanitarian outcomes.

1. Introduction

Climate change and patterns of vulnerability and exposure are altering characteristics and impacts of extreme weather events. It is increasingly clear that different sectors must prepare for extreme weather that has not previously been experienced, can be imagined only with difficulty, and poses risks of significant humanitarian impact for vulnerable communities – for the purposes of this work, we term it "unprecedented weather", a definition of which will be developed throughout the paper. The study of this risk is an emerging topic of research, and with this, there is an opportunity to ensure the science which emerges is useful and usable for disaster management.

This paper is the first, to our knowledge, to offer a specific dialogue on the topic of unprecedented weather between humanitarian practitioners and climate scientists. Its major aims are 1) To review the research landscapes on unprecedented weather and 2) To propose a working definition and typology about unprecedented weather which would be salient for both climate science and disaster management efforts and 3) To open a door for future collaborative work on this topic.

We employed a mixed methods approach to achieve these objectives. First, we explored different theoretical framings which guide current conceptual understandings of unprecedented weather. Next, we conducted a scoping literature of 406 peer-reviewed articles which we qualitatively coded for recurring themes. The results from the literature reviews were then brought to a workshop of 48 humanitarian practitioners to discuss practitioner concerns about unprecedented weather, preparedness requirements, and the resonance of the current research landscape for disaster management purposes.

The strands resulting from this process were consolidated into a proposed working definition and typology of unprecedented weather for climate scientists and humanitarian disaster management practitioners. Our work shows that current science does not reflect the diversity of humanitarian sector concerns about unprecedented weather risks, and that opportunities abound to design research which can lead to better disaster preparedness and humanitarian outcomes.

2. Methods

2.1. Narrative and scoping literature reviews

Literature reviews are valuable tools to investigate the state of scholarship for a particular topic [1]. Distinct types of reviews exist with specific uses: systematic literature reviews follow replicable methodologies to authoritatively evaluate an established body of research [1] while narrative literature reviews focus on key pieces of research and can be used to develop conceptual framings about a topic. Scoping studies fall in the middle, using a determined methodology to explore a question, uncover key themes, and analyse gaps of a certain research field [1].

For this paper, we adapted methods outlined by Pham et al. [1] to a mixed-methods approach, comprising both a narrative review with snowball sampling for the paper's conceptual section and a scoping literature review for the paper's analytical results.

For the scoping review, we selected 406 peer-reviewed articles which use the term "unprecedented" to refer to hydrometeorological events. We qualitatively coded these articles in NVivo based on methods described by Saldaña [2] to answer three key questions:

Is the term "unprecedented" used to refer to one or more specific weather events? (n = 254/406).
Does the paper provide a defined geographic and/or temporal reference point to the term "unprecedented"? (n = 158/406).

Scoping Literature Review Process
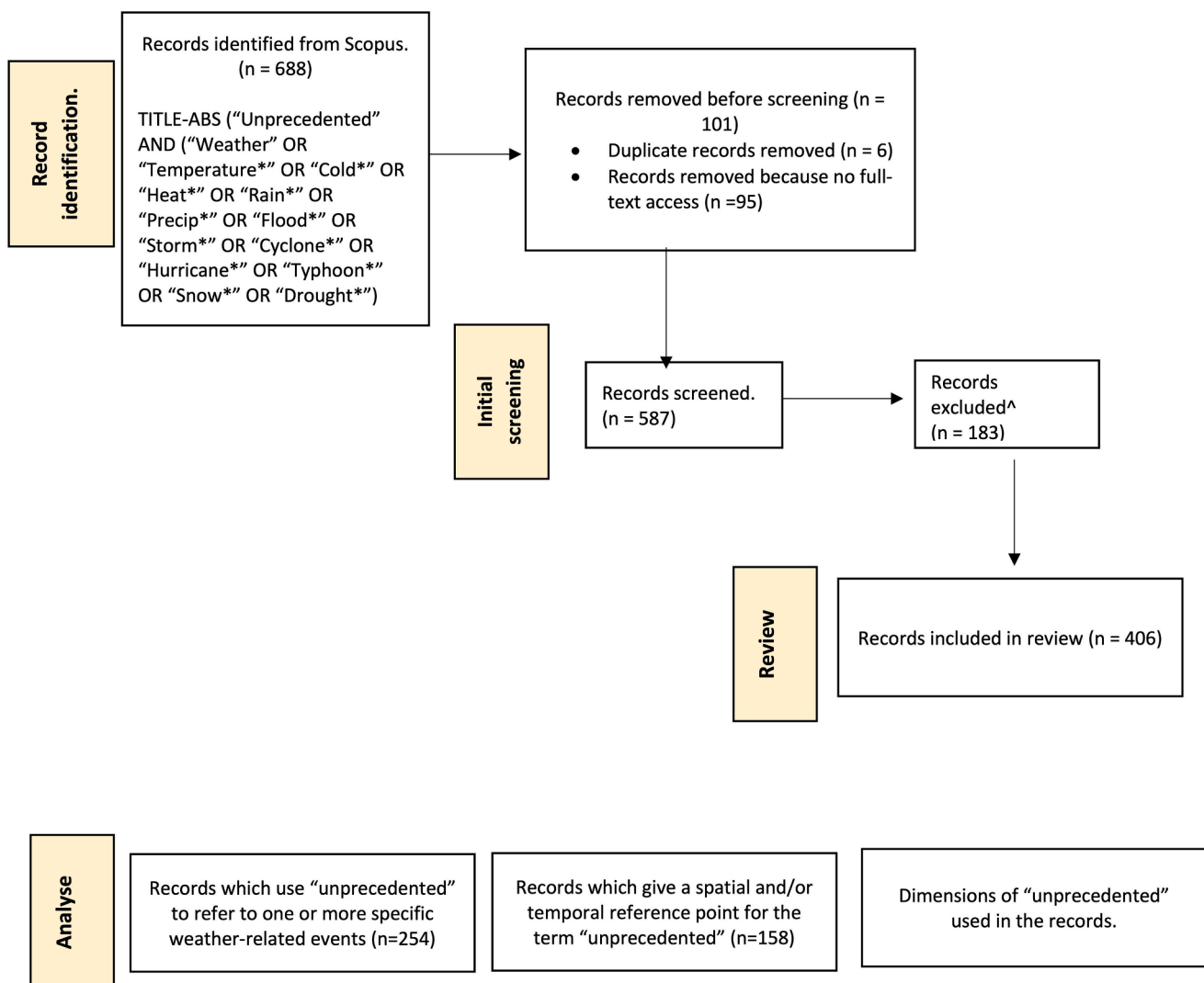
^ Papers were excluded if weather was not a key topic of the research. Note that many of the papers excluded came from materials engineering and had slipped into the research terms because of the inclusion of the term "heat" which was not being used in those papers to refer to a weather-related event.

Fig. 1. Prisma Diagram for our scoping literature review. Adapted from Page et al. [125].

What are the diverse ways in which the term "unprecedented" refers to these events? *This last set of codes identified the key themes used as dimensions for our typology of unprecedented weather.*

Details of our search terms and Prisma diagram can be found in Fig. 1, our bibliography in supplementary data, and we summarize our results in the section below.

A limitation of this method was the decision made to constrain the search to the term "unprecedented" rather than other related phrases such as "record-breaking" [3], unusual, or "exceptional" [4]. As the research landscape grows, a follow-up study could explore how all these terms are used and defined in different ways.

2.2. Expert elicitation workshop with humanitarian practitioners

Once the literature reviews were completed, we ran an online workshop with 48 humanitarian disaster management practitioners from Africa, Asia, Europe, and North and South America, all experts in disaster management design, logistics, and implementation. The workshop took place online on February 1st, 2024 on the Anticipation Hub, a community of organisations operating in the space of early warning and anticipatory action. In the workshop, we posed questions to participants and led a semi-structure discussion with the aim to reflect on literature review results, identify more examples of past unprecedented events, discuss disaster management challenges and opportunities, and identify requests for climate science research on the topic. Ethics approval was provided by the School of Mathematics, Physical and Computational Sciences at the University of Reading.

2.3. Working definition and typology development

We consolidated the results from both literature reviews and the workshop to build a working definition and typology of unprecedented weather with the aim to guide towards a more precise and salient understanding of unprecedented weather risks for humanitarian disaster management.

Definition and typology development is a method used in many disciplines to organize concepts around a common definition. For instance, some typologies categorize unprecedented non-weather events (e.g. [5–7]), different types of weather-related hazards [8–10], and disasters more generally [11–12].

For our typology, we adapted theory and methodology by Collier et al. [13] with iterative validation with climate scientists and humanitarian practitioners. The results from each method informed in turn the format, content, and relevance of the working definition and typology: the narrative review provided the conceptual part of the working definition while the themes from the coded scoping review provided the typology's dimensions and variables. These results were then reviewed through the expert elicitation process to shape the final version of the working definition and typology. Table 1 shows the logical flow of the paper's structure.

Our definition was bolstered by Cattiaux and Ribes [14] who offer a quantitative method to define single extreme weather events in time and

space. The disaster management angle of our typology was also inspired by Mackay et al. [15], Berren et al. [8], and Gundel [16]. Mackay et al. [15] and Hsu [11] both provided insights for wording of spatial and temporal dimensions, and a comprehensive typology about compound events by Zscheischler et al. [10] guided the addition of compound risks to our dimensions. The use of the term "unprecedented" in the IPCC's 6th Assessment Report influenced our articulation of different dimensions [17,132].

3. Results

3.1. Narrative literature review results: Conceptual framings

The Oxford English Dictionary defines "unprecedented" as "*having no precedent; unparalleled; never previously done, known, or experienced*", something which simply has never happened before [18]. The use of this term for weather-related events is similar. For instance, the IPCC's AR6 chapter on extreme weather notably uses the term in the following FAQ box:

> "Will unprecedented extremes occur as a result of human-induced climate change? As the climate moves away from its past and current states, we will experience extreme events that are unprecedented, either in magnitude, frequency, timing, or location. The frequency of these unprecedented extreme events will rise with increasing global warming. Additionally, the combined occurrence of multiple unprecedented extremes may result in large and unprecedented impacts." [132]

Initiatives to study unprecedented weather risks are increasing in various academic spaces as well. For instance, the development of the UNSEEN network [127] and events like a 2023 workshop summarised in Matte et al. [20] are bringing together cross-disciplinary scholarship into a community of research on this topic. A rapid increase in the number of academic articles about unprecedented weather, particularly in climate science and environmental fields, can be seen in Fig. 2.

For this section, we build a narrative review which examines how unprecedented events have been conceptualised by different disciplines. Other works has reviewed methodological approaches to studying these risks (e.g. [4,20]). For our purposes, these conceptual distinctions offer insights into nested discourse and terminology which we can take to define and typologize unprecedented weather.

3.1.1. Unprecedented weather as outliers in observational records or climate models

First, unprecedented weather can be conceptualised as a statistical anomaly or outlier, some measure of distance from the norm [21–23]. Research which falls under this umbrella is strongly quantitative and conceptualises unprecedented weather as outliers in observational records or climate models, and various statistical approaches have been developed to analyse these.

In traditional statistics, outliers were often seen as dataset error that reduced the quality of the analysis, and therefore could be removed to avoid skewing results [21,24–25]. Increasingly, however, statisticians

Table 1
Methodology and paper structure.

| Process (adapted from [13]	Method	Aim	Results and sections	Figures
Identify dimensions and variables. Design typology matrix	Scoping literature review with thematic coding	Identify dimensions and variables given to unprecedented weather in the literature.	3.2. Scoping literature review: thematic analysis	Fig. 3 and Table 2.
Develop and validate	Humanitarian practitionner workshop	Gather practitioner perspectives of definitions and dimensions of unprecedented weather. Highlight humanitarian concerns and preparedness implications.	3.3. Expert elicitation: humanitarian practitioner perspectives	Table 3 and Fig. 4
Finalise	Consolidation of literature review and workshop results	Bring together science and practitioner perspectives towards a common definition and typology of unprecedented weather.	4. Working definition and typology	Fig. 5
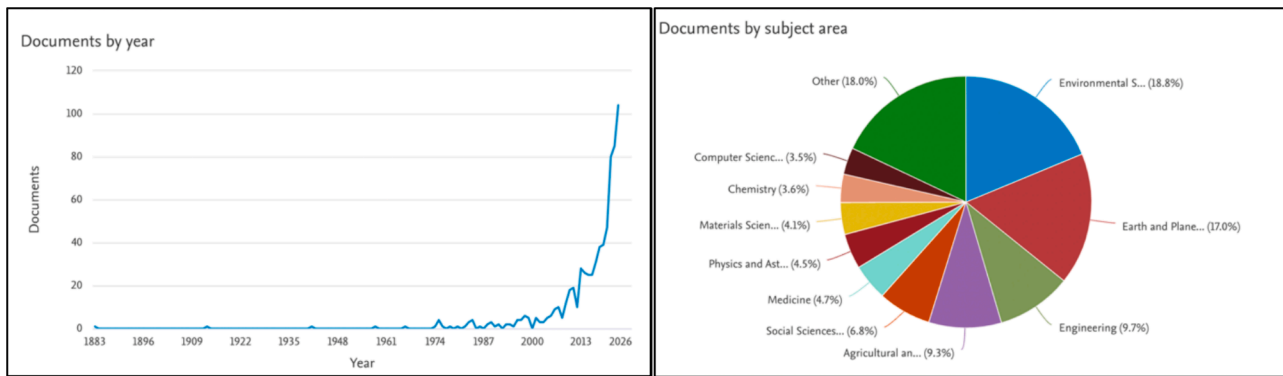
Fig. 2. Characteristics articles sampled for the scoping literature review for this paper, showing a rapid increase in the number of articles on the topic (left) and within these a main disciplinary focus in earth and environmental sciences (right). Figures from Scopus.

have argued that outliers may be windows into unprecedented but plausible elements of the data [21,24–26]. Various methods exist to detect and describe outliers in observational weather records. For example, the World Meteorological Organization formally evaluates records of climate extremes around the world, providing precise geographic location, date, and record length [27] and some extreme event attribution and/or analysis initiatives explore analogue events from various sources such as merged station and satellite data [28–29]. However, observational records, even merged data, can be short and sparse [30–31]. To fill these gaps, certain statistical methods have been developed to estimate return periods beyond observational records such as making use of Generalized Extreme Value distributions and large deviation theory [32–34]. Reanalysis datasets have also been used as a proxy to identify plausible extremes beyond observational records [35], and generative weather models (both dynamical and statistical) have been used to create synthetic but plausible events (e.g. [36–39]).

Fischer et al. [40] note that is it relatively easier to identify past outlier events than future risks: "*it is challenging to identify the type and definition of unprecedented events to look for, including the time and spatial scales, before they happen*". Various approaches are being developed to address this issue. Key in this landscape are climate storyline approaches which attempt to understand the plausibility, rather than probability of unprecedented events [41–45]. For example, the UNSEEN protocol was developed to expand the limits of climate models through the use of forecast ensembles [19,26,46,47] and ensemble boosting approaches have been used to replicate heatwave conditions previously thought impossible [40]. Some work has also been done to compare storylines developed through various statistical and dynamical modelling methods, notably for exceptional heatwaves [48].

3.1.2. Unprecedented weather as high-impact-low-probability

Building from this, another group of literature adds an impact angle to the outlier concept, characterising some extreme events as "high-impact-low probability" (HILP) [49–51]. This is terminology often found in the engineering sector, particularly for energy and infrastructure, and notably illustrates something about the vulnerability and exposure of infrastructure or people at risk. The premise here is that it is specifically the "low probability" which causes the high impact; the fact that it is an outlier makes it impactful. Impacts occur when existing preparedness is insufficient, notably because of limited risk perception, short-term disaster management practices, and general epistemic uncertainty about the probability or plausibility of these events [52–53]. This conceptualisation is often used to highlight the importance of understanding risks of rare extreme events because they will have severe consequences. For example, the UNSEEN approach described above has been applied to argue the foreseeability of low-probability impactful heatwaves [26]. A relatively large body of literature focuses on high-impact weather more broadly, without these necessarily framed as

having a low-probability. There is notably a range of work on forecasts and early warnings for high impact weather [54–56], for instance through the World Weather Research Programme's High Impact Weather [57].

3.1.3. Unprecedented weather as black swan events

A final theoretical angle is provided by the common conceptualisation of certain unprecedented events as "black swans". This points to the foreseeability of rare events, and literature using this terminology typically explores case studies of extremes events that have been surprising and highly impactful. The "black swan" can be a helpful frame to understand that the foreseeability and perception of (im)plausibility of unprecedented events can be a determinant of preparedness and the level of impacts that these events can have.

The origin of the expression "Black Swan" to denote something impossible has been linked the Ancient Roman poet Juvenal [58–59]. Before 1697, when Willem de Vlamingh happened upon black swans in Australia, all swans known to Europeans where white – from then, in Europe, the term "black swan" began to mean something previously thought impossible but eventually proven by its occurrence [58]–in order words, no number of observations of white swans could totally disprove the existence of black ones [59]. This was notably central to philosopher Karl Popper's seminal theories about falsification [60]. In the 21st century, Taleb popularised the term in his book, *The Black Swan: The Impact of the Highly Improbable*. In this, he defines Black Swan events by three specific attributes: an extreme outlier, that causes impact and cannot be predicted (but often is followed by post-event explanations). Since the publication of Taleb's book, the term Black Swan has been used extensively across diverse disciplines to refer to unprecedented events, the uncertainty and surprise when they occur, and the severe impacts they can have for this reason [6,61]: "*this lack of preparation represents a lack of experience and/or psychological readiness to deal with events so massive that they defy imagination, and the extent to which the scale of such events might overwhelm even the best-laid plans*." [62].

From this, many related concepts have emerged, such as "dragon kings" to refer to even more extreme outliers with unique properties [63–64] or "grey swans" to refer to events that are within plausibility from natural variability but are currently outside the observational record [124]. These Black Swan metaphors have found themselves used to characterise extreme weather events in multiple instances [61,64–65], and the combination of black swan theory with climate services are also used for disaster management planning. For instance, the co-development downward counterfactual scenarios have both made use of climate information [66–68] and been used to inform physical climate storylines [69]. The perceived un-foreseeability of black swans has also been central to the development of methodological approaches such as UNSEEN [26] to make foreseen these events, and therefore turn them from black swans to known risks for which we can prepare.

3.2. Scoping literature review results: Thematic analysis

3.2.1. General findings

Among the 406 articles in our scoping review, over 50 % use the term "unprecedented" to refer to a specific or set of weather events which have occurred in the past. Among these, heatwaves and droughts are the most frequently studied hazards, followed by wildfires, storms, and extreme precipitation, and finally by cold waves and/or snowfall. Certain past events are recurrently qualified as unprecedented – notably, the 2015 Hurricane Harvey (USA), the 2015–2016 Australia bushfires, the 2015 Mumbai floods (India), the 2021 Pakistan floods, and the 2021 Pacific Northwest Heatwave (USA/Canada). Research which uses the term "unprecedented" to refer to future risk often relates to climate projections showing increases in record-breaking temperatures (e.g. [70–71]), projections of drought (e.g. [72]), or changes in storm characteristics (e.g. [73–74]).

Next, there are key distinctions made between events that are unprecedented in the observational record (which for some types of hazards and locations can be quite sparse) and risks that are unprecedented even in model data. A few papers in the literature sampled state their objective to identify if a particular event was truly unprecedented. For example, Dhar et al. [75] ask "*Was the July 1981 rainstorm over Rajasthan unprecedented*?" and Doss-Goslin et al. [76]: "*How unprecedented was the February 2021 Texas cold snap?*". These papers clearly define their usage of the term, often noting a spatial and temporal framing such as defining the years of the observational record and drawing a geographic box around the area in question to see the uniqueness of the event. As contrast, some authors warn of an overuse and lack of clarity of the term unprecedented. For example, Muir [77] describes a rainfall event in Ontario, Canada: "*Under this skewed risk perspective, a high-profile Ontario commuter train flood was mischaracterized as an unprecedented event despite a < 5 y return period and a greater flood weeks before.*".

Finally, it is striking that very little research mentions the implications of these unprecedented events for disaster management. A few notable exceptions are Kreibich et al. [78] and Nielsen-Gammon et al. [79] who state "[*unprecedented drought risk…] presents unprecedented challenges for water managers and stakeholders, as well as unprecedented data needs*". Similarly, there is little quantification of unprecedented impacts or vulnerability and exposure contexts. This mirrors documented gaps whereby humanitarian disaster management practices do not often find themselves in academic literature [126] and the limits of disaster impact data more generally.

3.2.2. Thematic findings

Our thematic coding of our literature sample shows at least ten different ways in which the term "unprecedented" is used to refer to past weather-related events or future risk (Fig. 3 and Table 3).

First, as seen in Fig. 3, there is an overwhelming focus of research on the unprecedented hazard magnitude including record-breaking rainfall amounts (e.g. [80–82] or highest and lowest recorded temperatures (e.g. [42,70]). Quantification of this magnitude is often connected to the calculation of the return-periods of hazard conditions.

Next, a smaller proportion of literature focuses on hazard extent, often expressed in distance measurements. For example, this dimension is used to describe the number of hectares burned by wildfires (e.g. [83–85]) or a record proportion of a country affected (e.g.[86]). A handful of papers also refer to unprecedented location: for example, Newman-Thacker and Turnbull [87] talk about unusual wildfires burning near the Chernobyl reactor in 2020. Articles also look at unprecedented hazard duration – droughts (e.g. [81,88]) and heatwaves (e.g. [89–90]) are most often described in this way, expressed in days, weeks, or months. A handful of papers also explore the unprecedented timing or frequency of events, examining occurrence compared to usual seasonality. These dimensions can also occur at the same time. For example, Lin et al. [91] observe the early rainy summer in China and Sloane et al. [92] characterise temperatures "*unprecedented in both extremity and timing*".

Finally, many articles in the sample use the term "unprecedented" to refer to the context in which extreme events have occurred and which therefore had significant impact due to heightened vulnerability and exposure. For instance, research refers to the unprecedented combination of multiple shocks which are either connected or not (e.g. [93–94]). For example, Shakoor et al. [95] describe: "*Since March 2023, Canada has been grappling with an unprecedented succession of wildfires, which have notably intensified in June. This wildfire season has shattered previous records, making it the most severe in Canada's documented history (Dion 2023). Furthermore, it is anticipated that Canada will experience its largest area ever affected by wildfires this year.*" Additionally, over twenty papers reviewed refer to unprecedented impacts (e.g. [96–99]) of specific events but it is rare to find a geographic or temporal qualifier to this usage which reflects well documented gaps in recording and comparing disaster impacts.

Table 2 shows each of these eight themes with example quotes from the literature sampled.

3.3. Expert elicitation results: Humanitarian practitioner perspectives

Moving from the literature, our expert elicitation process provided key insights into the perspectives of humanitarian disaster management practitioners who are at the forefront of preparing and responding to unprecedented weather.

During the workshop, participants were first asked to define unprecedented weather in a way that resonates most with them. For this, they were asked to choose a hazard type with which they were familiar and then imagine what an unprecedented version might look like. Table 3 records some of these definitions and illustrates the diversity in which practitioners define unprecedented weather.

The discussion that followed these definitions, resonated with much of the theory described in our narrative review above – the boundaries of statistical outliers, the uncertainty of the Black Swans, and the high-impact. One participant typified these conversations in saying: "*I think it's really interesting to see the different levels of how people define unprecedented or define it in their head (…)*" Participants defined unprecedented weather as "*something that is hopefully unimaginable*" or "*unprecedented, because society had never imagined it would happen*" The notion of humanitarian impacts provided a read thread throughout: "*an unprecedented hazard in a place where nobody lives is […] less of an issue*".

A recurring theme, which was missing from the literature review, was the potential subjectivity of the term "unprecedented": it depends on for whom, where and when this is defined, and this can change. For example, one participant asked: "*Would it still be considered unprecedented if historically an event had been recorded by a HydroMet institution but the population, say the elders, have no living memory of it? Who would define this?*" Similarly, someone else asked: "*What about the population group the disaster strikes – if they never have experienced before, would [it] be unprecedented?*". For instance, refugee or migrant populations who have recently moved to new places may not have experience with certain types of hazards – as such, an extreme weather event can be unprecedented for them, and they are significantly more vulnerable than people who have lived in that area for longer and are therefore more likely to be prepared. Similarly, population growth or conflict may rapidly change the vulnerability profiles, or the sheer number of people exposed to extreme weather in that location and therefore heighten the potential for unprecedented impacts. A hazard can also be common for a country or region but unusual for certain locations within it: "*even if a country as a whole has experience with a hazard but it's in a new location […] that's a really different experience*": for instance, Mozambique has detailed national preparedness plans for cyclones but if a storm makes landfall in an unusual part of the country that is not generally considered at risk, local preparedness systems may be lacking. All these questions about experience and perception-based preparedness find echoes in our literature review where not all papers defined a temporal or location

Frequency of coded articles by theme
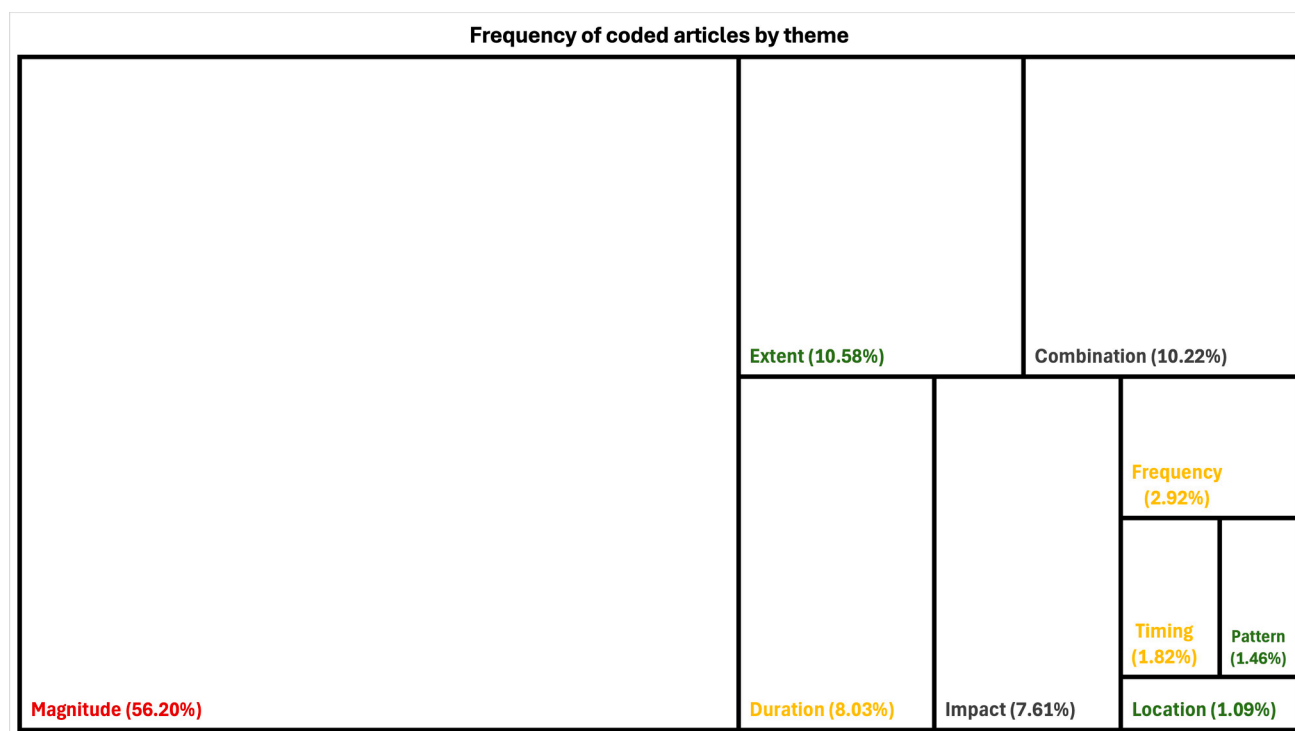
Fig. 3. Frequency of articles coded by theme. The size of the boxes relates to the proportion of articles which use the term "unprecedented" in a certain way to refer to a hydrometeorological event or risk. This illustrates that the largest proportion of articles reviewed focus on hazard magnitude whilst the other dimensions are much less common. The colours refer to the grouping made of these codes in Table 4.

Table 2
Illustrative quotes for each of the main literature review codes.

Theme	Example
Magnitude	*"This extreme HPE [High Precipitation Event] on 26 July 2005 was **unprecedented due to the observed magnitude** of 94.4 cm over isolated localities in the northeast parts Mumbai City (…)"* [111].
Duration	*" "In the spring of 2011, the stage of the Richelieu River (Figure 1) largely exceeded all the previous floods, with a peak river discharge reaching 20% above the previous record **lasting for more than two months above the flood threshold**(1,064 m³/s) (Riboust and Brissette 2016). [...] This flood was unprecedented in terms of intensity and **duration**" [...]* [130]
Timing	*"These temperatures were unprecedented both in extremity and in **timing**. In previous years, mean daily maximum temperatures during the Bushtit breeding season from approximately late March to mid-July ranged from 10 °C to 38 °C. **At no time** in any previous breeding season did air temperatures rise above 38 °C (NOAA 2021)."* [92]
Frequency	*"Thus, the **frequency** of extreme warm season precipitation events in this region has increased during the last 1–2 decades to levels unprecedented in the historical record."* [112]
Location	*"In the summer of 2022, unprecedented Indian monsoon waves reached **higher latitudes**, resulting in heavy rainfall and flooding in Pakistan and Iran."* [128].
Extent	*"California's 2020 wildfire season (July-November) resulted in the burning of 1.8 million hectares or 4 % of the state's territory (one-tenth of Australia's total), making it the most **extensive** California wildfire season in the modern record (…)"* [129]
Combination	*"The flood was a culmination of a season of **unprecedented harsh weather**–the worst winter ever recorded, with 8 different blizzards, excessive snow, and subzero temperatures. Unfortunately, residents fought not only a flood but also a year of rain, ice, snow, wind, and cold."* [113]
Impact	*"Hurricane Katrina caused unprecedented **damage** to New Orleans, Louisiana, by flooding 80 % of the city. Katrina was the costliest hurricane in US history and caused $17 billion in damages in Orleans Parish (county equivalent) alone. Katrina also caused more deaths in Louisiana (n = 1170) than in any other Gulf Coast state."* [96].

Table 3
Definitions of unprecedented weather-related events given by the workshop participants.

Choose a hazard…	… imagine it unprecedented.
Storm	*"A storm longer than usual (days), higher wind, more rain, more flooding (new areas flood, higher levels of flood waters)"*
Storm surge	*"Cape Town coastline experiencing storm surge higher than a two-story building."*
Drought	*"A drought lasting over 6 consecutive rainfall seasons."*
Cold wave	*"A frigid cold snap in a place in a warm or tropical location which doesn't usually experience seasonality."*
Heatwave	*"Heatwaves become so intense that we have oven like temperatures on earth, it's impossible for human beings to go outside and if they do their skin burns off. Animal and plant life cannot survive."*
Flooding	*"A flood that occurs after the monsoon season, affecting the harvest."*
Heatwave	*"Heatwaves lasting over a longer time period (more than 10 days), with sustained temperatures over 38 degrees Celsius. With impacts on basic infrastructure (electricity, transportation), health, etc."*
Cyclone	*"Wind speeds and storm surges with a TC that is even higher than with Hayian so like e.g. 10 m storm surge, leading to consecutive coastal floods, all combined leading to enormous impact."*
Storm	*"After years of droughts, rivers are no longer as deep and unable to allow rainwater to seep in. A sudden, unprecedented thunderstorm created extreme flash floods that caught pedestrians unaware."*
Vector-borne diseases	*"People are getting bitten by mosquitos. They don't know that they can contain dengue now. No one has any idea what the symptoms of dengue are. People wait to get treated as they don't know what to do."*

reference point to their use of the term. These reference points clearly matter for disaster management.

Next, participants defined various dimensions in which an extreme weather event would be considered unprecedented far beyond the magnitude of a hazard. Notably, they perceived unprecedented events as a function of vulnerability of certain places and communities exposed to single or compound hazards which cause severe impacts – as one

participant termed it: "*a series of unfortunate events that lead to something that is unprecedented.*". The unprecedented duration of extreme weather are also a significant concern for their humanitarian impacts– for example, one participant offered the example of cyclone Freddy (Southern Africa, 2023 – to date longest lasting tropical cyclone active for 37 days) – "*I see [cyclone Freddy] as unprecedented as it came once and went out and came back again (…) it was really unprecedented because people in Malawi thought 'ok, this is it, it's over', and then it all came back once more.*" The speed of event onset and ability to forecast it in a timely manner was also mentioned as key for early warning and anticipatory action: "*I think "speed" is an important one […and…] encompasses the possibility that the meteorological systems simply fail to be able to forecast an event which goes well beyond something previously experienced, or the forecasts are not believed.*".

It was clear from the conversations that preparing for unprecedented weather of diverse dimensions is a significant challenge for humanitarian practitioners for which usable science would be valued. Workshop participants underscored that unprecedented weather is a significant humanitarian concern and for which general preparedness is lacking. As one participant wrote: "*Might a more circumspect view be that folks are not as prepared as they think they are?*". Whilst the humanitarian sector has many tools to prepare to respond for extreme weather events (e.g. simulation exercises, counterfactual workshops, multi-hazard contingency planning), the imagination that is required [100], and the trade-offs to prepare for events previously unseen entails significant barriers (see Fig. 4). From participants highlighted that different dimensions of unprecedented weather would have significantly different implications for disaster management: for example, responding to a cyclone of unprecedented duration would require more human resources to sustain operations and preparing for a cyclone of unprecedented magnitude would require more infrastructure strengthening activities.

Finally, participants in the workshop also highlighted barriers to prepare for unprecedented events and requests for ways to address these. Notably, a perception of uncertainty, trade-offs and competing priorities, and the reactive and inflexible structure of the sector which makes preparing for many unprecedented scenarios difficult. Communication of unimaginable risks is also a significant issue. As one participant said: "*I wonder if one of the biggest challenges is actually convincing others […] that these kinds of events are plausible and should be prepared for.*

[…] I think sometimes communities are better at imagination than institutions." Worries of unnecessarily alarming was also mentioned, and echoes fears of false alarms which some say can decrease trust: "*We have to consider the risk of ending as Cassandra [the Ancient Greek priestess whose disaster prophecies were never believed]*". Scale and granularity of information can also be an issue, and practitioners made requests for risk knowledge as "*localised answers, scaled-down versions of whatever you are doing. Don't tell me what is happening to the world but what could/would happen to my locality.*".

4. Consolidation: A working definition and typology

Defining singular extreme weather events is a known challenge which requires precision and a clear framing as it will have implications on any science [14] or practice. From the combination of both literature reviews and the humanitarian practitioner workshop, we can see emerge a working qualitative definition of unprecedented weather.

1. Unprecedented weather is a deviation from the record, an outlier in either or both quantitative (e.g. in return periods) or qualitative (e.g. in different dimensions) terms.
2. The risk of an unprecedented weather is characterised by a certain level of uncertainty due to limitations of observational records, climate modelling, and weather forecasting.
3. Unprecedented weather events are beyond what is expected or imagined by the people who experience or manage it– oftentimes, these types of events are under-prepared for, heightening concerns about their possible impact on vulnerable and exposure communities.
4. Definitions of unprecedented weather are bounded by a spatial, temporal, and perception reference point: unprecedented how, where, since when, and for whom are key questions to answer. It is essential to explicitly clarify the frame and definition which is being used to analyse past events and future risk.
5. A diverse and multidimensional understanding of unprecedented risk is critical for adapted disaster management.

From the themes identified above through the literature review and practitioner elicitation, we can build a typology for unprecedented
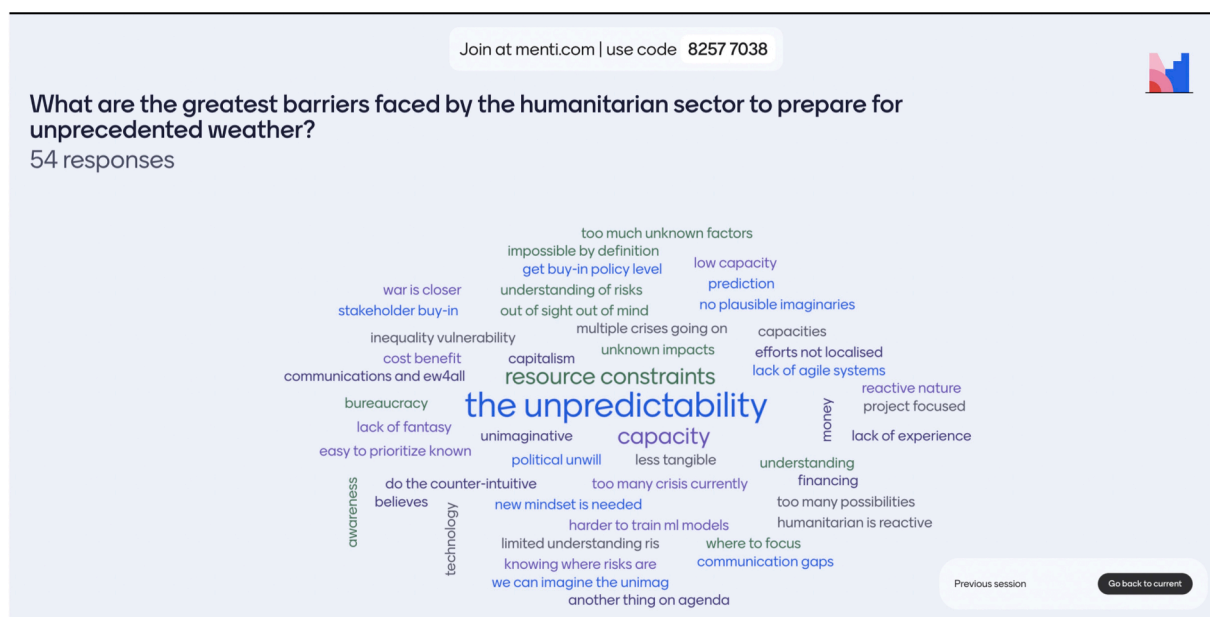
Fig. 4. A Mentimeter word cloud by participants in the workshop showing the strongest barriers to preparing for unprecedented weather. Perceptions of unpredictability and capacity and source constraints were particularly emphasized.

weather. We suggest that extreme weather can be unprecedented in *degree* (magnitude, intensity), time (duration, timing, frequency, speed), and *space* (location, extent, pattern). Although beyond the scope of this paper, many contextual conditions can also be unprecedented, notably if events are cascading or compounding, or occur in new vulnerability and exposure contexts. Some dimensions may be more common for certain types of hazards than others and can interact.[1]

Table 4 below details these dimensions and variables and offers descriptions and example events for each type.

5. Discussion

Our findings show humanitarian practitioners are concerned about unprecedented events in more diverse ways than science currently investigates. As such, the topic is ripe with opportunities for collaboration between climate scientists and disaster managers to articulate and answer key questions about current and future weather-related risks. Developing co-production methods for these conversations is critical to ensure more usable research and bridge the usability gap [101–103]. Specifically for unprecedented weather, seminal work on co-produced climate narratives and storylines can offer inspiration [104].

First, our literature review finds that there is a lot of research describing past unprecedented weather, but humanitarian practitioners are more concerned with current and future risks. In the context of rapid climate change, this gap is critical and reflects Fischer et al. [40] who explain that it is easier to build storylines of past unprecedented weather because the complexity of decisions which need to be made to model plausible unprecedented futures. With event definition being a crucial first step for a range of approaches [26,46,105–106] our working typology could provide a benchmark to facilitate these decisions – guiding the definition of a geographic box (unprecedented where?), a clear time period (unprecedented since when and for whom?), and diverse dimensions (unprecedented how?). There could be a significant opportunity here for collaboration between scientists and practitioners to build more salient definitions of unprecedented hazard of different dimensions to develop storylines for scenario-planning. For instance, *what geographic box should we draw around our analysis which would be most relevant for disaster management? How far back should we look in our records to define an event as unprecedented? For whom are we concerned this type of hazard be unprecedented?*

Second, our results show that most climate science currently investigates the unprecedented magnitude of extreme weather which leaves understudied many risks which may, in fact, matter more for humanitarian outcomes. There is a strong demand by the practitioners to extend research to risks that would be unprecedented in more diverse dimensions and at scales that resonate with disaster management requirements. For instance, humanitarian practitioners resonate strongly with questions about unprecedented duration, timing, and extent of extreme weather but the literature reviewed showed a disproportionate emphasis of study on the magnitude dimension compared to the others. These gaps could be filled by new types of climate storylines research at local and regional levels to answer questions such as: *What places in the world might be at current risks of certain types and dimensions of extreme weather but do not know it because they have been lucky? What are plausible storylines for a tropical cyclone or a heatwave unprecedented in duration, extent, or timing for which local disaster management systems may be underprepared?*

Third, a more diverse understanding of unprecedented weather is necessary for enhanced disaster management in very concrete ways.

Humanitarian disaster preparedness systems are likely to be under-prepared to anticipate and respond to unprecedented weather events [107–109] and because extreme weather can have unprecedented impacts without the hazard itself being unusual, as a function of high vulnerability and limited preparedness. While it is true that the sector already makes extensive use of scenarios and simulations to prepare for different risks, these are often based on previously experienced events. Robust storylines of plausible current and future risks of unprecedented weather of all the dimensions of the typology could be used to build these scenarios and develop adapted early warning messages, anticipatory action protocols, and disaster response contingency plans to cover a wider range of risks. This could be a rich field of work for scientists and practitioners, and could be inspired by work on net-zero scenarios [110] and the development of downward counterfactuals of natural hazards [68]. Research and practice questions could resemble: *how can we use science, storytelling, or games to increase imagination of weather risks that this community has never seen before but is known to be highly plausible in the current climate? What would be good early warning messages for unprecedented weather events and would lead to appropriate action be taken? What would be the resilience of current contingency plans and early action protocols if these were confronted with weather events that would be unprecedented in different dimensions?*

Overarchingly, our results uncover a requirement for imagination: more imaginative climate science can better support disaster management by increasing knowledge about the diverse risks of unprecedented weather in vulnerable locations and for vulnerable people. A concrete opportunity exists here to improve the understanding, uptake, and usability of physical climate storylines of unprecedented weather for disaster management planning with the aim to reduce humanitarian impacts.

6. Conclusions

Despite the significant humanitarian risks posed by unprecedented weather, it is a challenge for scientists and practitioners to discuss these risks without a common definition and understanding. In this paper, we combine narrative and scoping literature reviews of more than 400 scientific articles with an expert elicitation process with 48 humanitarian practitioners to develop a working definition and typology which we hope can help lead to more usable science for disaster management. A summary illustration of this definition and typology can be found in Fig. 5.

The main conclusions of this paper can be summarized in the following way.

1. Unprecedented weather events pose risks of significant humanitarian impacts and is a growing research topic in climate science disciplines.
2. Humanitarian practitioners are concerned about current and future risks of unprecedented weather, and emerging climate science approaches can help answer some of the most pressing questions.
3. There is currently a large focus of research on events of unprecedented magnitude but there are many other dimensions in which weather can be unprecedented, all which have different implications for disaster management.down
4. We offer here a working definition and typology of unprecedented weather to support collaborations between climate scientists and disaster management practitioners in the humanitarian sector and beyond.

We conclude this piece with a call for more imaginative and usable research on unprecedented weather risks. A science-practice dialogue on this topic is essential to supporting decision-making in a rapidly changing climate. While this paper focused on humanitarian perspectives, *all* sectors are required to build resilience to unprecedented weather and will have different asks for climate services. A whole-of-

---

[1] For example, at the moment of finalising this paper, Hurricane Beryl has made headlines for being the earliest Category 5 Atlantic hurricane on record as well as the "strongest and easternmost hurricane" recorded in the basin in June [123], an illustration of how dimensions can overlap to create a significantly impactful event.

Table 4
Suggested typology of unprecedented weather.

	Dimensions	Hazard variables	Description	Possibly illustrative events[a]
Unprecedented how, where, since when, for whom…	Degree	Magnitude	The hazard conditions are quantifiably higher over a period.	2021. North America. Pacific Northwest Heatwave. Temperature records shattered, for instance in Lytton, British Columbia [42,114]
		Intensity	The hazard occurs with higher and in another qualitatively severe way at a given time.	2015. Hurricane Patricia. Multiple records broken including highest maximum sustained winds in the Western Hemisphere [131].
	Time	Duration	The hazard lasts longer.	February/March 2023. Southern Africa. Cyclone Freddy. Longest lasting tropical cyclone on record with 5 weeks and 2 days [115].
		Timing	The hazard occurs at a different time of the year.	2021. Nepal. Out-of-season floods. Floods past the monsoon withdrawal date [116].
		Frequency	There is a higher frequency of occurrence of the same type of hazard.	2005. Most hurricanes in a year with 15 recorded by the USA National Hurricane Centre [117]
		Speed	The speed of onset or intensification of the hazard is faster.	2022. Pacific. Cyclone of record rapid intensification and intensity [74].
	Space	Location	The type of hazard occurs in a new location.	1900. Texas, USA. Galveston Hurricane. First hurricane to ever hit Texas and remains deadliest weather-related disaster in the USA [118]
		Extent	The hazard is larger and/or occurs over a larger geographic scale.	2019/2020. Australia. "Black Summer" wildfires [83].
		Pattern	The hazard occurs with a different geographic clustering.	2016. Tropical Andes. Precipitation events during El Nino across the region [119].
	Context – (beyond the scope of this paper)	Cascading or compound shocks	Overlapping hazards occur at the same time or one after the other, exacerbating each other. For this, readers can refer notably to the typology by Zscheischler et al. [10].	2022. Pakistan. Exceptional drought and flooding experienced in the same year [120].
		Vulnerability and exposure conditions	Hazards occurring in a new heightened context of vulnerability and exposure and can create unprecedented impacts (whether or not the hazard conditions are unprecedented).	2020. Bangladesh. Cyclone Amphan hits the country during an unprecedented global pandemic [121–123].

[a]It is key to note that the illustrative events originate from the reviewed literature where they were described as unprecedented in these different dimensions but we have not conducted any further analysis on these events for this paper.
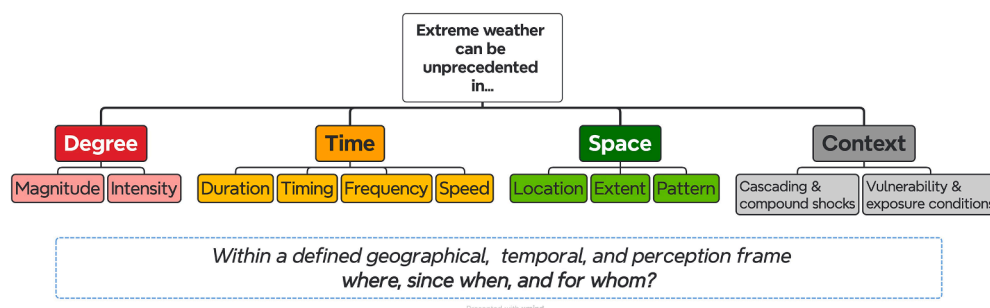
Fig. 5. Summary figure showing the typology dimensions and variables, and our proposed working definition for unprecedented weather hazards. Our results suggest that the degree dimension is disproportionately emphasized in current climate science research and that unprecedented time and space matter significantly for humanitarian disaster management.

society approach to imagining, understanding, and addressing these risks is essential.

CRediT authorship contribution statement

Dorothy Heinrich: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Elisabeth Stephens:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Erin Coughlan de Perez:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Acknowledgements

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasec.2024.100181.

References

[1] M.T. Pham, A. Rajić, J.D. Greig, J.M. Sargeant, A. Papadopoulos, S.A. McEwen, A scoping review of scoping reviews: advancing the approach and enhancing the consistency, Res. Synth. Methods 5 (4) (2014) 371–385, https://doi.org/10.1002/jrsm.1123.

[2] J. Saldana, Thinking Qualitatively: Methods of Mind, SAGE Publications, 2014.

[3] R. Vautard, M. van Aalst, O. Boucher, A. Drouin, K. Haustein, F. Kreienkamp, G. J. van Oldenborgh, F.E.L. Otto, A. Ribes, Y. Robin, M. Schneider, J.-M. Soubeyroux, P. Stott, S.I. Seneviratne, M.M. Vogel, M. Wehner, Human contribution to the record-breaking June and July 2019 heatwaves in Western Europe, Environ. Res. Lett. 15 (9) (2020) 094077, https://doi.org/10.1088/1748-9326/aba3d4.

[4] Kelder, T., Klok, L., Slater, L., Thompson, V., Goulart, H. M. D., Suarez-Gutierrez, L., Wilby, R., Heinrich, D., Perez, E. C. de, Stephens, L., Hawkins, E., Burt, S., Hurk, B. van den, Vries, H. de, Wiel, K. van der, Fischer, E., 2024a. Anticipating the unseen: A community review on how to better prepare for exceptional weather events (EGU24-7944). EGU24. Copernicus Meetings. doi: 10.5194/egusphere-egu24-7944.

[5] Maes, M. A., Dann, M. R., 2017. Freak Events, Black Swans, and Unknowable Unknowns: Impact on Risk-Based Design. In R. Caspeele, L. Taerwe, & D. Proske (Eds.), 14th International Probabilistic Workshop (pp. 15–30). Springer International Publishing. doi: 10.1007/978-3-319-47886-9_2.

[6] E. Paté-Cornell, On "Black Swans" and "Perfect Storms": risk analysis and management when statistics are not enough, Risk Anal. 32 (11) (2012) 1823–1833, https://doi.org/10.1111/j.1539-6924.2011.01787.x.

[7] S. Piperca, S. Floricel, A typology of unexpected events in complex projects, Int. J. Manag. Proj. Bus. 5 (2) (2012) 248–265, https://doi.org/10.1108/17538371211214932.

[8] M.R. Berren, A. Beigel, G. Barker, A typology for the classification of disasters: Implications for intervention, Community Ment. Health J. 18 (2) (1982) 120–134, https://doi.org/10.1007/BF00754456.

[9] B.J. Clarke, E.L.F. Otto, R.G. Jones, Inventories of extreme weather events and impacts: Implications for loss and damage from and adaptation to climate extremes, Clim. Risk Manag. 32 (2021) 100285, https://doi.org/10.1016/j.crm.2021.100285.

[10] J. Zscheischler, O. Martius, S. Westra, E. Bevacqua, C. Raymond, R.M. Horton, B. van den Hurk, A. AghaKouchak, A. Jézéquel, M.D. Mahecha, D. Maraun, A. M. Ramos, N.N. Ridder, W. Thiery, E. Vignotto, A typology of compound weather and climate events, Article 7, Nature Reviews Earth & Environment 1 (7) (2020), https://doi.org/10.1038/s43017-020-0060-z.

[11] E.L. Hsu, Must disasters be rapidly occurring? The case for an expanded temporal typology of disasters, Scopus, Time Soc. 28 (3) (2019) 904–921, https://doi.org/10.1177/0961463X17701956.

[12] D. Teh, T. Khan, Types, definition and classification of natural disasters and threat level, in: Handbook of Disaster Risk Reduction for Resilience: New Frameworks for Building Resilience to Disasters, Scopus, 2021, pp. 27–56, https://doi.org/10.1007/978-3-030-61278-8_2.

[13] D. Collier, J. LaPorte, J. Seawright, Putting typologies to work: concept formation, measurement, and analytic rigor, Polit. Res. q. 65 (1) (2012) 217–232, https://doi.org/10.1177/1065912912437162.

[14] J. Cattiaux, A. Ribes, Defining Single Extreme Weather Events in a Climate Perspective, (2018), https://doi.org/10.1175/BAMS-D-17-0281.1.

[15] J. Mackay, A. Munoz, M. Pepper, A disaster typology towards informing humanitarian relief supply chain design, Scopus, Journal of Humanitarian Logistics and Supply Chain Management 9 (1) (2019) 22–46, https://doi.org/10.1108/JHLSCM-06-2018-0049.

[16] S. Gundel, Towards a New Typology of Crises, J. Conting. Crisis Manag. 13 (3) (2005) 106–115, https://doi.org/10.1111/j.1468-5973.2005.00465.x.

[17] IPCC. (2023). Climate Change 2023: Synthesis Report. (Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]).

[18] Oxford English Dictionary. (n.d.). Unprecedented. Retrieved March 29, 2024, from https://www.oed.com/dictionary/unprecedented_adj.

[19] T. Kelder, N. Wanders, K. van der Wiel, T.I. Marjoribanks, L.J. Slater, R. Wilby, C. Prudhomme, Interpreting extreme climate impacts from large ensemble simulations—are they unseen or unrealistic? Environ. Res. Lett. 17 (4) (2022) 044052 https://doi.org/10.1088/1748-9326/ac5cf4.

[20] D. Matte, J.H. Christensen, M. Drews, S. Sobolowski, D. Paquin, A. Lynch, S. Bremer, I. Engholm, N.D. Brunet, E.W. Kolstad, H. Kettleborough, V. Thompson, E. Bevacqua, D. Heinrich, S.C. Pryor, A. Böhnisch, F. Feser, A. F. Prein, E. Fischer, M. Leduc, How to Engage and Adapt to Unprecedented Extremes. (2024), https://doi.org/10.1175/BAMS-D-24-0138.1.

[21] R. Foorthuis, On the nature and types of anomalies: A review of deviations in data, International Journal of Data Science and Analytics 12 (4) (2021) 297–331, https://doi.org/10.1007/s41060-021-00265-1.

[22] D.M. Hawkins, Identification of Outliers, Springer, Netherlands. (1980), https://doi.org/10.1007/978-94-015-3994-4.

[23] A. Smiti, A critical overview of outlier detection methods, Computer Science Review 38 (2020) 100306, https://doi.org/10.1016/j.cosrev.2020.100306.

[24] D. Bailey, Why OUTLIERS are good for science, Significance 15 (1) (2018) 14–19, https://doi.org/10.1111/j.1740-9713.2018.01105.x.

[25] J. Chen, S. Abbady, M.B. Duggimpudi, Spatiotemporal Outlier Detection: Did Buoys Tell Where the Hurricanes Were? Papers in Applied Geography 2 (3) (2016) 298–314, https://doi.org/10.1080/23754931.2016.1149874.

[26] T. Kelder, T.I. Marjoribanks, L.J. Slater, C. Prudhomme, R.L. Wilby, J. Wagemann, N. Dunstone, An open workflow to gain insights about low-likelihood high-impact weather events from initialized predictions, Meteorol. Appl. 29 (3) (2022) e2065.

[27] Records of Weather and Climate Extremes Table, n.d. World Meteorological Organization. Retrieved March 28, 2024, from https://wmo.int/files/records-of-weather-and-climate-extremes-table.

[28] D. Faranda, S. Bourdin, M. Ginesta, M. Krouma, R. Noyelle, F. Pons, P. Yiou, G. Messori, A climate-change attribution retrospective of some impactful weather extremes of 2021, Weather Climate Dyn. 3 (4) (2022) 1311–1340, https://doi.org/10.5194/wcd-3-1311-2022.

[29] D. Faranda, G. Messori, E. Coppola, T. Alberti, M. Vrac, F. Pons, P. Yiou, LuM. Saint, A.N.S. Hisi, P. Brockmann, S. Dafis, R. Vautard, ClimaMeter: Contextualising Extreme Weather in a Changing Climate, Egusphere 1–34 (2023), https://doi.org/10.5194/egusphere-2023-2643.

[30] J. Nightingale, J.P.D. Mittaz, S. Douglas, D. Dee, J. Ryder, M. Taylor, C. Old, C. Dieval, C. Fouron, G. Duveau, C. Merchant, Ten priority science gaps in assessing climate data record quality, Article 8, Remote Sens. (Basel) 11 (8) (2019), https://doi.org/10.3390/rs11080986.

[31] D. Walker, N. Forsythe, G. Parkin, J. Gowing, Filling the observational void: Scientific value and quantitative validation of hydrometeorological data from a community-based monitoring programme, J. Hydrol. 538 (2016) 713–725, https://doi.org/10.1016/j.jhydrol.2016.04.062.

[32] M. Charras-Garrido, P. Lezaud, Extreme Value Analysis: An Introduction, Journal De La Société Française De Statistique 154 (2) (2013) 66–97.

[33] R.A. Fisher, L.H.C. Tippett, Limiting forms of the frequency distribution of the largest or smallest member of a sample, Math. Proc. Camb. Philos. Soc. 24 (2) (1928) 180–190, https://doi.org/10.1017/S0305004100015681.

[34] V.M. Galfi, V. Lucarini, Fingerprinting heatwaves and cold spells and assessing their response to climate change using large deviation theory, Phys. Rev. Lett. 127 (5) (2021) 058701, https://doi.org/10.1103/PhysRevLett.127.058701.

[35] J. Cattiaux, A. Ribes, V. Thompson, Searching for the Most Extreme Temperature Events in Recent History. (2024), https://doi.org/10.1175/BAMS-D-23-0095.1.

[36] N. Bloemendaal, I.D. Haigh, H. de Moel, S. Muis, R.J. Haarsma, J.C.J.H. Aerts, Generation of a global synthetic tropical cyclone hazard dataset using STORM, Sci. Data 7 (1) (2020) 40, https://doi.org/10.1038/s41597-020-0381-2.

[37] M.I. Brunner, E. Gilleland, A. Wood, D.L. Swain, M. Clark, Spatial dependence of floods shaped by spatiotemporal variations in meteorological and land-surface processes, Geophys. Res. Lett. 47 (13) (2020) e2020GL088000, https://doi.org/10.1029/2020GL088000.

[38] N. Sparks, R. Toumi, The Imperial College Storm Model (IRIS) Dataset, Scopus, Sci. Data 11 (1) (2024), https://doi.org/10.1038/s41597-024-03250-y.

[39] G. Villarini, W. Zhang, P. Miller, D.R. Johnson, L.E. Grimley, H.J. Roberts, Probabilistic rainfall generator for tropical cyclones affecting Louisiana, Int. J. Climatol. 42 (3) (2022) 1789–1802, https://doi.org/10.1002/joc.7335.

[40] E.M. Fischer, U. Beyerle, L. Bloin-Wibe, C. Gessner, V. Humphrey, F. Lehner, A. G. Pendergrass, S. Sippel, J. Zeder, R. Knutti, Storylines for unprecedented heatwaves based on ensemble boosting, Article 1, Nat. Commun. 14 (1) (2023), https://doi.org/10.1038/s41467-023-40112-4.

[41] E. Baulenas, G. Versteeg, M. Terrado, J. Mindlin, D. Bojovic, Assembling the climate story: Use of storyline approaches in climate-related science, Global Chall. (2023) 2200183, https://doi.org/10.1002/gch2.202200183.

[42] E. Fischer, The record-shattering 2021 Pacific Northwest heatwave – challenges and opportunities for attribution and event storylines (EGU23-11732), EGU23. Copernicus Meetings. (2023), https://doi.org/10.5194/egusphere-egu23-11732.

[43] T.G. Shepherd, The dynamics of temperature extremes, Article 7557, Nature 522 (7557) (2015), https://doi.org/10.1038/522450a.

[44] T.G. Shepherd, E. Boyd, R.A. Calel, S.C. Chapman, S. Dessai, I.M. Dima-West, H. J. Fowler, R. James, D. Maraun, O. Martius, C.A. Senior, A.H. Sobel, D. A. Stainforth, S.F.B. Tett, K.E. Trenberth, B.J.J.M. van den Hurk, N.W. Watkins, R. L. Wilby, D.A. Zenghelis, Storylines: An alternative approach to representing

uncertainty in physical aspects of climate change, Clim. Change 151 (3) (2018) 555–571, https://doi.org/10.1007/s10584-018-2317-9.

[45] H.R. Young, T.G. Shepherd, J. Acidri, R.J. Cornforth, C. Petty, J. Seaman, L. C. Todman, Storylines for decision-making: Climate and food security in Namibia, Clim. Dev. 13 (6) (2021) 515–528, https://doi.org/10.1080/17565529.2020.1808438.

[46] E. Coughlan de Perez, H. Ganapathi, G.I.T. Masukwedza, T. Griffin, T. Kelder, Potential for surprising heat and drought events in wheat-producing regions of USA and China, Article 1, Npj Clim. Atmos. Sci. 6 (1) (2023), https://doi.org/10.1038/s41612-023-00361-y.

[47] V. Thompson, N.J. Dunstone, A.A. Scaife, D.M. Smith, J.M. Slingo, S. Brown, S. E. Belcher, High risk of unprecedented UK rainfall in the current climate, Scopus, Nat. Commun. 8 (1) (2017), https://doi.org/10.1038/s41467-017-00275-3.

[48] C. Gessner, E.M. Fischer, U. Beyerle, R. Knutti, Very Rare Heat Extremes: Quantifying and Understanding Using Ensemble Reinitialization. (2021), https://doi.org/10.1175/JCLI-D-20-0916.1.

[49] Bridger, N.J., 2019. High impact, low probability risk and related events in political rsk analysis: An evaluation of the Black Swan [Thesis, Stellenbosch : Stellenbosch University]. https://scholar.sun.ac.za:443/handle/10019.1/105877.

[50] A.J. White, Thinking about the "Practically Unthinkable": energy infrastructure and the threat of low-probability, High-Impact Events 12 (3) (2011).

[51] J. Yeo, L. Comfort, An expected event, but unprecedented damage: Structure and gaps of large-scale response coordination of the 2011 Thailand floods, Disaster Prevention and Management: an International Journal 26 (4) (2017) 458–470, https://doi.org/10.1108/DPM-02-2017-0048.

[52] Lee, B., Preston, F., 2012. Preparing for High-impact, Low-probability Events (ISBN 978 1 86203 253 8). Chatham House (Royal Institute of International Affairs.

[53] R.M. Rauber, J.E. Walsh, D.J. Charlevoix, Severe and Hazardous Weather: An Introduction to High Impact Meteorology, Kendall Hunt Publishing Co., 2017.

[54] Legg, T.P., Mylne, K.R., 2004. Early Warnings of Severe Weather from Ensemble Forecast Information. https://journals.ametsoc.org/view/journals/wefo/19/5/1520-0434_2004_019_0891_ewoswf_{20}_co_2.xml.

[55] S.J. Majumdar, J. Sun, B. Golding, P. Joe, J. Dudhia, O. Caumont, K.C. Gouda, P. Steinle, B. Vincendon, J. Wang, N. Yussouf, Multiscale Forecasting of High-Impact Weather: Current Status and Future Challenges. (2021), https://doi.org/10.1175/BAMS-D-20-0111.1.

[56] A.L. Taylor, T. Kox, D. Johnston, Communicating high impact weather: Improving warnings and decision making processes, Int. J. Disaster Risk Reduct. 30 (2018) 1–4, https://doi.org/10.1016/j.ijdrr.2018.04.002.

[57] B. Golding, Reducing the impact of high impact weather, Mausam 74 (2) (2023), https://doi.org/10.54302/mausam.v74i2.5980.

[58] B.J.M. Ale, D.N.D. Hartford, D.H. Slater, Dragons, black swans and decisions, Environ. Res. 183 (2020) 109127, https://doi.org/10.1016/j.envres.2020.109127.

[59] N.N. Taleb, The Black Swan, Random House, 2007.

[60] M.F. Duggan, Looking for Black Swans: Critical Elimination and History, Symposion 8 (1) (2021) 45–77, https://doi.org/10.5840/symposion2021812.

[61] I. Glette-Iversen, T. Aven, On the meaning of and relationship between dragon-kings, black swans and related concepts, Reliab. Eng. Syst. Saf. 211 (2021) 107625, https://doi.org/10.1016/j.ress.2021.107625.

[62] P.H. Phan, G. Wood, Doomsday Scenarios (or the Black Swan Excuse for Unpreparedness), Acad. Manag. Perspect. 34 (4) (2020) 425–433, https://doi.org/10.5465/amp.2020.0133.

[63] Sornette, D. (2009). Dragon-Kings, Black Swans and the Prediction of Crises (SSRN Scholarly Paper 1596032). doi: 10.2139/ssrn.1596032.

[64] D. Sornette, G. Ouillon, Dragon-kings: Mechanisms, statistical methods and empirical evidence, The European Physical Journal Special Topics 205 (1) (2012) 1–26, https://doi.org/10.1140/epjst/e2012-01559-5.

[65] M. Süveges, A.C. Davison, A case study of a "Dragon-King": The 1999 Venezuelan catastrophe, The European Physical Journal Special Topics 205 (1) (2012) 131–146, https://doi.org/10.1140/epjst/e2012-01566-6.

[66] Rabonza, M. L., Lin, Y. C., & Lallemant, D. (2022). Learning From Success, Not Catastrophe: Using Counterfactual Analysis to Highlight Successful Disaster Risk Reduction Interventions. Frontiers in Earth Science, 10. https://www.frontiersin.org/articles/10.3389/feart.2022.847196.

[67] Wilson, N., Payne, B., Kerr, J., Boyd, M., 2023. Embracing downward counterfactual analysis to navigate future cyclones. https://ourarchive.otago.ac.nz/handle/10523/15685.

[68] G. Woo, Downward counterfactual search for extreme events, Front. Earth Sci. 7 (2019). https://www.frontiersin.org/articles/10.3389/feart.2019.00340.

[69] A. Ciullo, O. Martius, E. Strobl, D.N. Bresch, A framework for building climate storylines based on downward counterfactuals: The case of the European Union Solidarity fund, Clim. Risk Manag. 33 (2021) 100349, https://doi.org/10.1016/j.crm.2021.100349.

[70] N. Christidis, D. Mitchell, P.A. Stott, Rapidly increasing likelihood of exceeding 50 °C in parts of the Mediterranean and the Middle East due to human influence, Scopus, Npj Clim. Atmos. Sci. 6 (1) (2023), https://doi.org/10.1038/s41612-023-00377-4.

[71] N.S. Diffenbaugh, M. Scherer, Observational and model evidence of global emergence of permanent, unprecedented heat in the 20th and 21st centuries, Scopus, Clim. Change 107 (3) (2011) 615–624, https://doi.org/10.1007/s10584-011-0112-y.

[72] B.I. Cook, T.R. Ault, J.E. Smerdon, Unprecedented 21st century drought risk in the American Southwest and Central Plains, Scopus, Sci. Adv. 1 (1) (2015), https://doi.org/10.1126/sciadv.1400082.

[73] A. Ganske, N. Fery, L. Gaslikova, I. Grabemann, R. Weisse, B. Tinz, Identification of extreme storm surges with high-impact potential along the German North Sea coastline, Scopus, Ocean Dyn. 68 (10) (2018) 1371–1382, https://doi.org/10.1007/s10236-018-1190-4.

[74] D. Xi, N. Lin, A. Gori, Increasing sequential tropical cyclone hazards along the US East and Gulf coasts, Nat. Clim. Chang. 13 (3) (2023) 258–265, https://doi.org/10.1038/s41558-023-01595-7.

[75] O.N. Dhar, P.R. Rakhecha, B.N. Mandal, R.B. Sangam, Was the July 1981 rainstorm over Rajasthan unprecedented? Pure and Applied Geophysics PAGEOPH, 120(3), 483–494, Scopus (1982), https://doi.org/10.1007/BF00879831.

[76] J. Doss-Gollin, D.J. Farnham, U. Lall, V. Modi, How unprecedented was the February 2021 Texas cold snap? Environ. Res. Lett. 16 (6) (2021) 064056 https://doi.org/10.1088/1748-9326/ac0278.

[77] Muir, R. J. (2018). Evidence based policy gaps in water resources: Thinking fast and slow on floods and flow. Journal of Water Management Modeling, 2018. Scopus. doi: 10.14796/JWMM.C449.

[78] H. Kreibich, A.F. Van Loon, K. Schröter, P.J. Ward, M. Mazzoleni, N. Sairam, G. W. Abeshu, S. Agafonova, A. AghaKouchak, H. Aksoy, C. Alvarez-Garreton, B. Aznar, L. Balkhi, M.H. Barendrecht, S. Biancamaria, L. Bos-Burgering, C. Bradley, Y. Budiyono, W. Buytaert, G. Di Baldassarre, The challenge of unprecedented floods and droughts in risk management, Article 7921, Nature 608 (7921) (2022), https://doi.org/10.1038/s41586-022-04917-5.

[79] J.W. Nielsen-Gammon, J.L. Banner, B.I. Cook, D.M. Tremaine, C.I. Wong, R. E. Mace, H. Gao, Z.-L. Yang, M.F. Gonzalez, R. Hoffpauir, T. Gooch, K. Kloesel, Unprecedented Drought Challenges for Texas Water Resources in a Changing Climate: What Do Researchers and Stakeholders Need to Know? Earth's Future, *8* (8), Scopus (2020), https://doi.org/10.1029/2020EF001552.

[80] E.-L. Blais, J. Greshuk, T. Stadnyk, The 2011 flood event in the Assiniboine River Basin: Causes, assessment and damages, Scopus, Canadian Water Resources Journal 41 (1–2) (2016) 74–84, https://doi.org/10.1080/07011784.2015.1046139.

[81] D. Griffin, K.J. Anchukaitis, How unusual is the 2012–2014 California drought?, Scopus, Geophys. Res. Lett. 41 (24) (2014) 9017–9023, https://doi.org/10.1002/2014GL062433.

[82] D. Keellings, J.J. Hernández Ayala, Extreme rainfall associated with Hurricane Maria over Puerto Rico and its connections to climate variability and change, Scopus, Geophys. Res. Lett. 46 (5) (2019) 2964–2973, https://doi.org/10.1029/2019GL082077.

[83] Clarke, B. Cirulism, T. Penman, O. Price, M.M. Boer, R. Bradstock, The 2019–2020 Australian forest fires are a harbinger of decreased prescribed burning effectiveness under rising extreme conditions, Scopus, Sci. Rep. 12 (1) (2022), https://doi.org/10.1038/s41598-022-15262-y.

[84] J. Cortes-Ramirez, R.N. Michael, L.D. Knibbs, H. Bambrick, M.R. Haswell, D. Wraith, The association of wildfire air pollution with COVID-19 incidence in New South Wales, Australia, Scopus, Sci. Total Environ. 809 (2022), https://doi.org/10.1016/j.scitotenv.2021.151158.

[85] T. Kraaij, J.A. Baard, J. Arndt, L. Vhengani, B.W. van Wilgen, An assessment of climate, weather, and fuel factors influencing a large, destructive wildfire in the Knysna region, South Africa, Scopus, Fire Ecology 14 (2) (2018), https://doi.org/10.1186/s42408-018-0001-0.

[86] P. Fox-Hughes, Synoptic and Mesoscale Aspects of Exceptional Fire Weather during the New Year Period 2019–20 in Southeastern New South Wales, Australia, Scopus, Weather Forecast. 38 (11) (2023) 2237–2252, https://doi.org/10.1175/WAF-D-23-0007.1.

[87] F. Newman-Thacker, L. Turnbull, Investigating the drivers of the unprecedented Chernobyl Power Plant Wildfire in April 2020 and its effects on 137Cs dispersal, Scopus, Nat. Hazards 109 (2) (2021) 1877–1897, https://doi.org/10.1007/s11069-021-04902-7.

[88] S.C. Ahumada, L.C. Suárez, R. Rivera, Could an event of extreme drought (2019–2020) affect the feeding ecology of Bubo magellanicus (Gmelin 1788) (Strigiformes: Strigidae) in a Mediterranean region of Chile?, Scopus, PeerJ 11 (2023), https://doi.org/10.7717/peerj.15020.

[89] D.A. Akompab, P. Bi, S. Williams, J. Grant, I.A. Walker, M. Augoustinos, Awareness of and attitudes towards heat waves within the context of climate change among a cohort of residents in Adelaide, Australia, Scopus, Int. J. Environ. Res. Public Health 10 (1) (2013), https://doi.org/10.3390/ijerph10010001.

[90] C. He, T. Zhou, L. Zhang, X. Chen, W. Zhang, Extremely hot East Asia and flooding western South Asia in the summer of 2022 tied to reversed flow over Tibetan Plateau, Scopus, Clim. Dyn. 61 (5–6) (2023) 2103–2119, https://doi.org/10.1007/s00382-023-06669-y.

[91] Y. Lin, Y. Fang, J. Wu, Z. Ke, C. Zhao, K. Tan, 2022: An Unprecedentedly Rainy Early Summer in Northeast China, Scopus, Atmos. 13 (10) (2022), https://doi.org/10.3390/atmos13101630.

[92] S.A. Sloane, A. Gordon, I.D. Connelly, Bushtit (Psaltriparus minimus) nestling mortality associated with unprecedented June 2021 heatwave in Portland, Scopus, Oregon. Wilson Journal of Ornithology 134 (1) (2022) 155–162, https://doi.org/10.1676/21-00080.

[93] N. Colombo, N. Guyennon, M. Valt, F. Salerno, D. Godone, P. Cianfarra, M. Freppaz, M. Maugeri, V. Manara, F. Acquaotta, A.B. Petrangeli, E. Romano, Unprecedented snow-drought conditions in the Italian Alps during the early 2020s, Scopus, Environ. Res. Lett. 18 (7) (2023), https://doi.org/10.1088/1748-9326/acdb88.

[94] M. Kemter, M. Fischer, L.V. Luna, E. Schönfeldt, J. Vogel, A. Banerjee, O. Korup, K. Thonicke, Cascading Hazards in the Aftermath of Australia's 2019/2020 Black Summer Wildfires, Scopus, Earth's Future 9 (3) (2021), https://doi.org/10.1029/2020EF001884.

[95] A. Shakoor, T.H. Farooq, M.S. Arif, S.M. Shahzad, Unprecedented wildfires in Canada and transboundary effects of carbon monoxide pollution, Scopus, Nat. Hazards 118 (3) (2023) 2711–2713, https://doi.org/10.1007/s11069-023-06117-4.

[96] J.H. Diaz, K.F. Brisolara, D.J. Harrington, C.-Y. Hu, A.L. Katner, The environmental health impact of Hurricane Katrina on New Orleans, Am. J. Public Health 110 (10) (2020) 1480–1484, https://doi.org/10.2105/AJPH.2020.305809.

[97] L. Head, J. Atchison, A. Gates, P. Muir, A fine-grained study of the experience of drought, risk and climate change among Australian wheat farming households, Scopus, Ann. Assoc. Am. Geogr. 101 (5) (2011) 1089–1108, https://doi.org/10.1080/00045608.2011.579533.

[98] M. Marchand, K. Gin, The Cardiovascular System in Heat Stroke, Scopus, CJC Open 4 (2) (2022) 158–163, https://doi.org/10.1016/j.cjco.2021.10.002.

[99] N. Ranger, S. Hallegatte, S. Bhattacharya, M. Bachu, S. Priya, K. Dhore, F. Rafique, P. Mathur, N. Naville, F. Henriet, C. Herweijer, S. Pohit, J. Corfee-Morlot, An assessment of the potential impact of climate change on flood risk in Mumbai, Scopus, Clim. Change 104 (1) (2011) 139–167, https://doi.org/10.1007/s10584-010-9979-2.

[100] J. Ommer, J. Neumann, M. Kalas, S. Blackburn, H.L. Cloke, Surprise floods: the role of our imagination in preparing for disasters, Egusphere 1–22 (2024), https://doi.org/10.5194/egusphere-2024-296.

[101] L. Dilling, M.C. Lemos, Creating usable science: Opportunities and constraints for climate knowledge use and their implications for science policy, Glob. Environ. Chang. 21 (2) (2011) 680–689, https://doi.org/10.1016/j.gloenvcha.2010.11.006.

[102] M.C. Lemos, C.J. Kirchhoff, V. Ramprasad, Narrowing the climate information usability gap, Article 11, Nat. Clim. Chang. 2 (11) (2012), https://doi.org/10.1038/nclimate1614.

[103] K. Raaphorst, G. Koers, G.J. Ellen, A. Oen, B. Kalsnes, L. van Well, J. Koerth, R. van der Brugge, Mind the gap: towards a typology of climate service usability gaps, Article 4, Sustainability 12 (4) (2020), https://doi.org/10.3390/su12041512.

[104] C.D. Jack, R. Jones, L. Burgin, J. Daron, Climate risk narratives: An iterative reflective process for co-producing and integrating climate knowledge, Clim. Risk Manag. 29 (2020) 100239, https://doi.org/10.1016/j.crm.2020.100239.

[105] S. Philip, S. Kew, G.J. van Oldenborgh, F. Otto, R. Vautard, K. van der Wiel, A. King, F. Lott, J. Arrighi, R. Singh, M. van Aalst, A protocol for probabilistic extreme event attribution analyses, Adv. Stat. Climatol. Meteorol. Oceanogr. 6 (2) (2020) 177–203, https://doi.org/10.5194/ascmo-6-177-2020.

[106] G.J. van Oldenborgh, K. van der Wiel, S. Kew, S. Philip, F. Otto, R. Vautard, A. King, F. Lott, J. Arrighi, R. Singh, M. van Aalst, Pathways and pitfalls in extreme event attribution, Clim. Change 166 (1) (2021) 13, https://doi.org/10.1007/s10584-021-03071-7.

[107] G. Endfield, S. Naylor, Climate and cultural heritage: An experiment with the 'Weather Memory, The Future of Heritage as Climates Change. (2015). https://www.taylorfrancis.com/chapters/edit/10.4324/9781315724164-12/climate-cultural-heritage-experiment-weather-memory-bank-georgina-endfield-simon-naylor.

[108] P. Weyrich, A. Scolobig, D.N. Bresch, A. Patt, Effects of impact-based warnings and behavioral recommendations for extreme weather events, Weather Clim. Soc. 10 (4) (2018) 781–796, https://doi.org/10.1175/WCAS-D-18-0038.1.

[109] C. Zanocco, H. Boudet, R. Nilson, H. Satein, H. Whitley, J. Flora, Place, proximity, and perceived harm: Extreme weather events and views about climate change, Clim. Change 149 (3) (2018) 349–365, https://doi.org/10.1007/s10584-018-2251-x.

[110] A.J. Dittus, M. Collins, R. Sutton, E. Hawkins, Reversal of Projected European Summer Precipitation Decline in a Stabilizing Climate, e2023GL107448, Geophys. Res. Lett. 51 (6) (2024), https://doi.org/10.1029/2023GL107448.

[111] V.B.R. Dodla, S.B. Ratna, Mesoscale characteristics and prediction of an unusual extreme heavy precipitation event over India using a high resolution mesoscale model, Scopus, Atmos. Res. 95 (2–3) (2010) 255–269, https://doi.org/10.1016/j.atmosres.2009.10.004.

[112] A.H. Matonse, A. Frei, A seasonal shift in the frequency of extreme hydrological events in Southern New York State, J. Clim. 26 (23) (2013) 9577–9593, https://doi.org/10.1175/JCLI-D-12-00810.1.

[113] E.P. Keene, Phenomenological study of the North Dakota flood experience and its impact on survivors' health, Int. J. Trauma Nurs. 4 (3) (1998) 79–84, https://doi.org/10.1016/s1075-4210(98)90073-6.

[114] V. Thompson, A.T. Kennedy-Asser, E. Vosper, Y.T.E. Lo, C. Huntingford, O. Andrews, M. Collins, G.C. Hegerl, D. Mitchell, The 2021 western North America heat wave among the most extreme events ever recorded globally, eabm6860, Sci. Adv. 8 (18) (2022), https://doi.org/10.1126/sciadv.abm6860.

[115] Liu, H.-Y., Satoh, M., Gu, J.-F., Lei, L., Tang, J., Tan, Z.-M., Wang, Y., Xu, J., 2023. Predictability of the Most Long-Lived Tropical Cyclone Freddy (2023) during its westward journey through the southern tropical indian ocean. Geophys. Res. Lett., 50(20), e2023GL105729. doi: 10.1029/2023GL105729.

[116] D. Bhandari, A. Dixit, Missed Opportunities in Utilization of Weather Forecasts: An Analysis of October 2021 Disaster in Nepal, ISET Nepal Publication, Nepal, 2022 https://isetnepal.org.np/wp-content/uploads/2022/03/Bhandari-and-Dixit-2022-Missed-Opportunities-in-Utilization-of-Weather-Forecasts-Nepal-ED.pdf.

[117] Colorado State University, n.d. North Atlantic Ocean Statistics compared with climatology. Retrieved March 29, 2024, from https://tropical.atmos.colostate.edu/Realtime/index.php?arch&loc=northatlantic.

[118] N.L. Frank, The Great Galveston Hurricane of 1900, in: Hurricane! Coping with Disaster: Progress and Challenges since Galveston, 1900, American Geophysical Union (AGU), 2003, pp. 128–140, https://doi.org/10.1029/SP055p0128.

[119] J. Sanabria, C.M. Carrillo, D. Labat, Unprecedented rainfall and moisture patterns during el nino 2016 in the eastern pacific and tropical andes: Northern peru and ecuador, Scopus, Atmos. 10 (12) (2019), https://doi.org/10.3390/ATMOS10120768.

[120] W. Ishaque, R. Tanvir, M. Mukhtar, Climate Change and Water Crises in Pakistan: Implications on Water Quality and Health Risks, Scopus, J. Environ. Public Health 2022 (2022), https://doi.org/10.1155/2022/5484561.

[121] M.S. Alam, T. Chakraborty, Understanding the nexus between public risk perception of COVID-19 and evacuation behavior during cyclone Amphan in Bangladesh, Heliyon 7 (7) (2021) e07655.

[122] D. Mitchell, L. Hawker, J. Savage, R. Bingham, N.S. Lord, M.J.U. Khan, P. Bates, F. Durand, A. Hassan, A.S. Islam, Y. Krien, J. Neal, C. Sampson, A. Smith, L. Testut, Increased population exposure to Amphan-scale cyclones under future climates, Clim. Resil. Sustain. 1 (2) (2022) e36.

[123] NASA, 2024. Beryl Becomes the First Major 2024 Atlantic Hurricane | NASA Global Precipitation Measurement Mission. https://gpm.nasa.gov/applications/weather/news/beryl-becomes-first-major-2024-atlantic-hurricane#:~:text=Beryl%20also%20became%20historic%20as,of%20Africa%20on%20June%2022.

[124] K. Horsburgh, I.D. Haigh, J. Williams, M. De Dominicis, J. Wolf, A. Inayatillah, D. Byrne, Grey swan" storm surges pose a greater coastal flood hazard than climate change, Ocean Dynam. 71 (6) (2021) 715–730, https://doi.org/10.1007/s10236-021-01453-0.

[125] M.J. Page, D. Moher, P.M. Bossuyt, I. Boutron, T.C. Hoffmann, C.D. Mulrow, L. Shamseer, J.M. Tetzlaff, E.A. Akl, S.E. Brennan, R. Chou, J. Glanville, J. M. Grimshaw, A. Hróbjartsson, M.M. Lalu, T. Li, E.W. Loder, E. Mayo-Wilson, S. McDonald, J.E. McKenzie, PRISMA 2020 explanation and elaboration: Updated guidance and exemplars for reporting systematic reviews, BMJ 372 (2021) n160, https://doi.org/10.1136/bmj.n160.

[126] A. Tozier de la Poterie, E. Castro, H. Rahaman, D. Heinrich, Y. Clatworthy, L. Mundorega, Anticipatory action to manage climate risks: Lessons from the Red Cross Red Crescent in Southern Africa, Bangladesh, and beyond, Climate Risk Manag. 39 (2023) 100476, https://doi.org/10.1016/j.crm.2023.100476.

[127] UNSEEN Network. Anticipating the Unseen Community Building to Better Prepare for Exceptional Weather Events An Initiative by the Convenors of the EGU Sessions on High-Impact Events*. https://storymaps.arcgis.com/stories/7f284f1d82d44a9489bfd76576e7d004.

[128] Z. Ghassabi, S. Karami, A. Vazifeh, M. Habibi, Investigating the unprecedented summer 2022 penetration of the Indian monsoon to Iran and evaluation of global and regional model forecasts, Dynam. Atmos. Ocean 103 (2023) 101386, https://doi.org/10.1016/j.dynatmoce.2023.101386.

[129] Sheehan, M. C. (2021). Climate Change and Human Well-Being in the 2020s: Lessons From 2020. *Int. J. Health Serv.*, *51*(3), 281–286. https://doi.org/10.1177/00207314211012155.

[130] Lucas-Picher, P., Lachance-Cloutier, S., Arsenault, R., Poulin, A., Ricard, S., Turcotte, R., & Brissette, F. (2021). Will Evolving Climate Conditions Increase the Risk of Floods of the Large U.S.-Canada Transboundary Richelieu River Basin? *J. Am. Water Res. Assoc.*, *57*(1), 32–56. https://doi.org/10.1111/1752-1688.12891.

[131] Rogers, R. F., Aberson, S., Bell, M. M., Cecil, D. J., Doyle, J. D., Kimberlain, T. B., Morgerman, J., Shay, L. K., & Velden, C. (2017). *Rewriting the Tropical Record Books: The Extraordinary Intensification of Hurricane Patricia (2015)*. https://doi.org/10.1175/BAMS-D-16-0039.1.

[132] S.I. Seneviratne, X. Zhang, M. Adnan, W. Badi, C. Dereczynski, A. Di Luca, S. Ghosh, I. Iskandar, J. Kossin, S. Lewis, F. Otto, I. Pinto, M. Satoh, S.M. Vicente-Serrano, M. Wehner, B. Zhou. Weather and Climate Extreme Events in a Changing Climate. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*[Masson-Delmotte], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2021, pp. 1513–1766, https://doi.org/10.1017/9781009157896.013.