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# Inventories of extreme weather events and impacts: Implications for loss and damage from and adaptation to climate extremes

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## ABSTRACT

Extreme and impactful weather events of the recent past provide a vital but under-utilised data source for understanding present and future climate risks. Extreme event attribution (EEA) enables us to quantify the influence of anthropogenic climate change (ACC) on a given event in a way that can be tailored to stakeholder needs, thereby enhancing the potential utility of studying past events. Here we set out a framework for systematically recording key details of high-impact events on a national scale (using the UK and Puerto Rico as examples), combining recent advances in event attribution with the risk framework. These ‘inventories’ inherently provide useful information depending on a user’s interest. For example, as a compilation of the impacts of ACC, we find that in the UK since 2000, at least 1500 excess deaths are directly attributable to human-induced climate change, while in Puerto Rico the increased intensity of Hurricane Maria alone led to the deaths of up to 3670 people. We also explore how inventories form a foundation for further analysis, learning from past events. This involves identifying the most damaging hazards and crucially also vulnerabilities and exposure characteristics over time. To build a risk assessment for heat-related mortality in the UK we focus on a vulnerable group, elderly urban populations, and project changes in the hazard and exposure within the same framework. Without improved preparedness, the risk to this group is likely to increase by ~50% by 2028 and ~150% by 2043. In addition, the framework allows the exploration of the likelihood of otherwise unprecedented events, or ‘Black Swans’. Finally, not only does it aid disaster preparedness and adaptation at local and national scales, such inventories also provide a new source of evidence for global stocktakes on adaptation and loss and damage such as mandated by the Paris Climate Agreement.

## 1. Introduction

Extreme weather of increasing intensity and frequency is the sharp edge of climate change (Coumou and Rahmstorf, 2012; Fischer and Knutti, 2015), posing a broad spectrum of evolving risks to societies around the world. Unprecedented heat waves threaten food supply chains (Welton, 2011) and pose a severe public health risk (Arbuthnott and Hajat, 2017; Mitchell et al., 2016), particularly to maladapted populations (Heaviside et al., 2016; Shaposhnikov et al., 2014). Rainfall and wind extremes from stronger storms lead to flooding and destroy property, lives and livelihoods (Houze et al., 2011; Schaller et al., 2016; Van Oldenborgh et al., 2017). This inflicts

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drastic impacts on the health, both mental and physical, of those affected (Fernandez et al., 2015; Paranjothy et al., 2011) as well as heavy economic disruption (Charterton et al., 2016; Pregolato et al., 2017). Moreover, multiple extremes may occur simultaneously or in rapid succession in the same location, thus exacerbating the severity of lived impacts (Zscheischler et al., 2018). Such ‘compound events’ are exceptionally difficult to plan for and are now undergoing dedicated study (AghaKouchak et al., 2014; Leonard et al., 2014; Zscheischler et al., 2020). The subtleties of changes in extremes in an irrefutably warming world are far from fully established, yet the overall signal and austere implications for society are clear (Hoegh-Guldberg et al., 2018).

However, anthropogenic climate change is far from the only contributor to changing extreme weather risks faced by people and property. Exposure and vulnerability to hazards are permanently in flux due to an ever-changing interplay of natural and human forces (Cardona et al., 2012). Furthermore, these contributions to risk all interact in a non-linear fashion and over diverse spatiotemporal scales (Birkmann and von Teichman, 2010). As such, while many individual contributing factors are reasonably predictable in a given locale, it is critical that their simultaneous evolution and relative magnitude are better understood. This would ensure that the science is best placed to inform future planning, given stakeholder interest (Ahmadalipour and Moradkhani, 2018; Byers et al., 2018; Duvat et al., 2017; Martín et al., 2017).

This work develops a new framework to improve understanding of changing risks from extreme weather. In the remainder of this section we home in on the most relevant literature upon which to build this framework and lay out the thought process behind its development. It could be argued that the exploration of climatic risks is largely a challenge for the impacts-modelling community, utilising projections of climate and socioeconomic development. However, in spite of recent developments, the field of literature assessing climate impacts still often focuses on trends in the mean in climate projections, rather than the drivers of risk from extremes (Burke et al., 2015; Hoegh-Guldberg et al., 2018; Kalkuhl and Wenz, 2020). In part, this is due to the large uncertainties in projected hazards, which forms the basis for all impacts projections and thus forms a weak foundation for further action. It is therefore proposed that additional work focusing specifically on rare but impactful events could add significant value. In line with this, we began with the young but expanding field of Extreme Event Attribution (EEA).

EEA enables researchers to estimate the change in likelihood and intensity of a specific, real-world weather event as a result of anthropogenic forcing in the climate system (Allen, 2003). By necessity, this is built upon a rigorous foundation of evidence relating to the event in question, a process that is steadily becoming formalised (Otto et al., 2020b). As a result, EEA provides a tangible bridge between the global phenomenon of climate change and the scales at which people live and decisions are made (Sippel et al., 2015). Moreover, through the choice of ‘event definition(s)’, it builds directly on lived experience of the event. Thus it enables effective communication of this link to non-expert stakeholders, from civil society to policymakers (Jézéquel et al., 2019; Otto et al., 2015), in turn forming an easily interpreted and more robust evidence base for planning resilience. Unfortunately, EEA studies are currently conducted on an ad-hoc basis, in part due to discrepancies in data availability in different regions (Huggel et al., 2016) but also the lack of comprehensive, coordinated efforts (Stott et al., 2016). They are also highly dependent upon the event definition used (Otto et al., 2016), and for some hazards struggle with deep uncertainties (Shepherd, 2016).

In short, EEA cannot (nor does it set out to) provide a silver-bullet method for attaining deep understanding of all changing risks from extreme weather. Nonetheless, as time passes by, the continued lack of serious mitigation effort means that the number of realisations of anthropogenically-amplified extreme weather is growing cumulatively (Herring et al., 2020, 2019, 2018, 2016, 2015, 2014; Peterson et al., 2015, 2012); there is already a substantial body of case studies from which to learn. This remains a vastly under-utilised resource, despite the evidence that a “societal actor’s prior experience of similar extreme weather events influences adaptive measures and preparedness for future extremes. An adequate description of the physical mechanisms and implications of relevant analogues from the past can positively influence adaptive capacity.” (Hazeleger et al., 2015). It is therefore critical that results from EEA are integrated with the knowledge of impacts collated by the insurance sector and NGOs, as well as insights from the Disaster Risk Reduction (DRR) community that deal more closely with the relationship between the meteorological extreme and experienced impacts. Collating such knowledge will optimise the potential practical applications of the science in a useful timeframe, particularly if efforts to build resilience are ramped up. It will also become ever more effective, and therefore pertinent, as EEA evolves into a standardised operational service (Stott et al., 2016).

Moreover, in addition to EEA, new approaches to risk analysis that capitalise on the wealth of information provided by case studies of past events are constantly emerging. For example, ‘storyline’ methods (Shepherd, 2015) enable exploration of the causal chain leading to an event (Daron et al., 2019), and are used to create bespoke narratives for various stakeholders (Hazeleger et al., 2015). This is complementary to the probabilistic approach as it is possible to gain useful information even when EEA analysis falls victim to prohibitively large uncertainties (Shepherd, 2016). Finally, it has also been proposed that exploring the physical boundaries of plausibility surrounding past events and near misses could provide insight into the possibility of highly destructive unprecedented events, or ‘black swans’ (Woo, 2019, 2016).

Overall, we conclude that a deeper knowledge of past events can underpin future understanding of, and preparation for, trends in extreme weather risk. Currently, however, a range of sources, including governments (Public Health England, 2013), reinsurance companies (Munich, 2018, 2016), media outlets, academic publications and NGOs (Muller, 2014) all keep records of past events and their impacts on an ad hoc basis. Even the most comprehensive and systematic hazard databases such as EMDAT (Guha-Sapir et al., 2014) are not built for the task of quantifying all loss and damage or relating this to anthropogenic climate change, much less disentangling all relevant drivers of disasters (Gall, 2015).

In order to bring together the relevant knowledge, we propose a standardised framework for recording historical impactful extreme weather events in an inventory structure. In particular, details of past events must be recorded alongside their key impacts, as well as other factors that fed into these impacts and finally any existing attribution literature to highlight the contribution from anthropogenic climate change (ACC). Critically, wherever possible the recording of impacts must include both quantifiable data and qualitative

information, and through both the immediate- and long-term. Furthermore, we suggest that such inventories provide maximum utility if compiled at the national scale as this is where the majority of stakeholders who are concerned with managing risk operate (Hoegh-Guldberg et al., 2018). In cases where risk management is largely the responsibility of more local powers, it is nonetheless beneficial for such policymakers to have access to other case studies outside their own jurisdiction but within a shared climatology. The national approach also aligns most closely with the remit of the Paris Agreement on adaptation, which aims to “follow a country-driven, gender-responsive, participatory and fully transparent approach” (Article 7).

To demonstrate the framework we present a inventories of past extreme weather events for the UK and Puerto Rico in the period 2000–2019. The UK was selected as the ideal initial location to explore this concept due to its substantial body of attribution literature, well-documented hazards and excellent record of observational data. Puerto Rico is presented as a counterpoint to this, being subjected to highly destructive tropical storms that present an array of additional challenges. Though the observational record of these impactful events is strong thanks to the island’s status as a US territory, the EEA literature for this region is extremely limited and the overall consensus on changing risks from climate change is still deeply uncertain. Furthermore, the deficiency of official estimates of mortality from Hurricane Maria (Kishore et al., 2018) highlighted possible systematic failures in the recording of such information from other disasters. The territory is therefore an emblematic case of ongoing and urgent risk management in the presence of high uncertainty.

The remainder of this paper is set out as follows. In Section 2 the process of creating and the inventories is explained and excerpts are presented. The main body of the paper is dedicated to the potential utility of this inventory concept. In Section 3 we focus on the applications of the work at national and sub-national scales, with an emphasis on risk management. This is further divided into two subsections: in 3.1 we explore results that are largely emergent from completed inventories, then in 3.2 we describe and present further analysis that uses inventories as a foundation. In Section 4 we discuss the implications of the work to the international community. Finally, in Section 5 we summarise our findings and propose pathways for future work to build on this.

## 2. The inventory

### 2.1. Process: ‘how to build an inventory of extreme weather events’

EMDAT is a global hazards database that provides information on impactful historical disasters, including meteorological, hydrological, epidemiological and even technological events (Guha-Sapir et al., 2014). Events are included in the database if the impacts meet at least one of the following criteria: 10 or more reported deaths, 100 or more people reported affected, a state of emergency declared, and/or a call for international assistance. Using the ‘disaster list’ feature, and specifying the UK and Puerto Rico as countries and the period 2000–2019 (inclusive) as the timeframe, we submitted a download request for all possible event and impact data. This data forms the basis of the inventory and a sample of data used for four UK events is provided in the [Supplementary material](#).

We then undertook a restructuring of the inventory to align with our central aim of providing a tool for exploring extreme weather events in more detail. We recognise that, in order to build up an accurate picture of how various factors contributed to the eventual impacts, it is critical to view the development of an event as a multi-stage causal chain. This ‘event narrative’ system facilitates the application of distinct framings for various analyses. For example, both a frequentist approach to the changing likelihood of the meteorological extreme and a highly conditional approach for probing different drivers of risk into the future would be supported in this system.

In the inventory, the ‘event narrative’ is divided into 3 components. Firstly, the meteorological conditions: here, the large-scale synoptic situation and ensuing formation of the often-extreme meteorology that triggered the event are detailed. Secondly, factors that compounded or helped to mitigate the eventual impacts on people are added. This could include topography, land-use, existing adaptation measures or the presence and effectiveness of warning systems, among a plethora of others. Finally, the narrative is concluded with details of any notable actions that were taken following an event. This includes both those to manage the longer-term impacts such as rehabilitation, and those to mitigate similar impacts in the future such as adaptation or improved warning systems.

Furthermore, to gain a more accurate perspective of the multitude of risks that extreme events pose to people and property, a wide range of impacts, both qualitative and quantitative, are considered. Thus, several of the specific impact data fields from EMDAT were amalgamated into a ‘miscellaneous impacts’ category with a broader scope to include both primary and secondary impacts, where documented. This contains notable data, such as numbers of homes flooded, people left without power and the local uptick in reported mental health issues, and also qualitative information where no quantities are quoted in reports. For example, during the UK summer drought of 2003, there were ‘fish fatalities and stress on other aquatic fauna’.

Finally, a section was created for EEA literature, which highlights the anthropogenic forcing component of the event. In order to provide maximum clarity, this section was subdivided into two. Firstly, the quantitative attribution statement itself. This takes the form of either a frequentist perspective, in the form of a FAR (fractional attributable risk) or PR (probability ratio) value, or a magnitude perspective, given by an amplification factor or magnitude change due to ACC. While the frequentist perspective enables a simpler calculation of attributable damages, the magnitude perspective provides both a clearer way of partitioning the effect on individual meteorological phenomena from a larger event and a causal link between ACC and lived impacts. The second subsection features a detailed explanation of the event definition and framing used in each study. Finally, as a point of clarification, ‘risk’ in the context of FAR refers only to hazard probability. This is distinct from the definition used throughout this work, which refers to an overlap of hazard probability, exposure and vulnerability. As such, FAR will only be used where absolutely necessary in reference to the studies that employ it.

With the restructuring complete, the process of ‘filling in’ the inventory began. This involved two aspects. Initially, we searched for events that may have been missed by EMDAT but which were, by the criteria above, still considered impactful. Secondly, we drew upon

a whole range of sources to ‘fill in the gaps’ in the inventory. These sources included academic papers from a range of fields including health impacts and EEA, official government reports and those from external government bodies (e.g. the Met Office, CEH, NOAA), reports from local councils, financial loss data from risk consultancies, other NGOs such as charities and disaster response organisations, and finally, failing other sources, media reports. While this system does not make the long-standing challenge of data curation easier or quicker, it both enables and encourages the collation of data from diverse sources and highlights where data is lacking.

Additional qualifying events were discovered through systematic research of the existing ones, which largely originated from the databases of National Met Services. For the UK, EMDAT provided 48 events and the final inventory contains 62, for the Puerto Rico, EMDAT provided 15 events and there are now 17. Furthermore, some new events, particularly windstorms ([PERILS AG](#)), lacked data on anything other than direct insured damages. It was therefore decided that a fifth criterion should be included; damage to property (insured or uninsured) and/or lost economic output over \$75 million. While it seems unlikely that any such event would fail to meet at least one of the other criteria, deficiencies in data reporting make this necessary in the framework to avoid rejecting important events. Inventories for both the UK and Puerto Rico can also be seen in the [Supplementary material](#).

Below is a brief step-by-step guide for creating inventories:

1. Download data from EMDAT using ‘disaster list’ feature and select location and timeframe of interest
2. Restructure table into inventory format and re-organise data
3. Fill in missing data with additional research into each event, adding any new qualifying events. Note: Some national Met Services provide an invaluable source of information on past events often missed by EMDAT.
4. Review attribution literature and fill in results – specifically, we suggest:
  - I. Begin with BAMS special reports
  - II. Follow up with Google Scholar or other literature databases using targeted keyword searches

## 2.2. Inventory definition

Overall, this inventory is a framework for recording historical events that are defined as impactful using a predefined threshold, and its purpose is highlighting the most relevant drivers of the impacts of these events, with implications for studying future risk through the lens of changing hazard, exposure and vulnerability.

There are several factors involved in defining which events are included in the inventory where criteria thresholds are to some degree arbitrary. For example, the losses crucially depend not only on the level of vulnerability and exposure but also on whether the event was forecasted and if the forecast was acted upon. Over time the implications of a static impact threshold method might also need to be questioned given the existence of adaptation measures. For instance, if such measures were successful in mitigating the final impacts of an event to below the required threshold, it would fail to be recorded. The inventory is therefore strictly defined as including impactful events above existing adaptive capacity at the time of occurrence. This definition adds a level of inherent bias in event selection, which may be important in the case of comparing different regions. In addition, some potential ‘near-miss’ case studies will be excluded. However, since the primary aim of the inventory is to provide a useful tool for highlighting and managing current and evolving risks, this is viewed as a necessary bias; the alternative would require some far more arbitrary definition of ‘impactful’.

Furthermore, the inclusion of EEA may create the impression that the inventory is a way of providing an overall assessment of the cost of climate change through its influence on impactful weather events. However, this is not the case. While trends and individual events can be linked to climate change through attribution science, simply adding up the fingerprint on all events that have happened is insufficient to provide a comprehensive picture of the ‘social cost of carbon’. There are many possible events, such as severe cold spells, that in some counterfactual scenario may have been sufficiently impactful to be recorded in the inventory, but as a result of anthropogenic forcing were made less extreme. Thus, in its ideal form, the inventory provides no more or no less than a breakdown of historical impactful events into various known factors that contributed towards the eventual impacts, including the anthropogenic climate forcing. As such it has significant value as an evidence base for engaged parties to identify actions that could enhance disaster resilience, and also to assess the losses and damages from anthropogenic climate change that have truly occurred.

## 3. Stakeholder applications

The majority of stakeholders interested in extreme weather risks operate at the national and sub-national scales. Previous research involving stakeholder participants suggests that “[EEA] might become a useful tool in the day-to-day work of adaptation planners or to bolster investment decisions” ([Sippel et al., 2015](#)). Thus for such prospective users, we propose two overarching benefits of this inventory. Firstly, it provides an assessment of historic extreme weather events resulting in losses and damages, alongside their relation to ACC. This allows for the first time an assessment of the impacts of climate change that have actually occurred and also a timeline of changes in these attributable losses and damages. Critically, this will help to close the gap between the tools currently used to inform climate policy and the actual damages being done, as highlighted by [Frame et al. \(2020b\)](#). Secondly, it offers the means for disentangling and identifying the drivers of changing hazards and losses, and allows linkages with how they are projected to change, at policy-relevant scales. The inventory therefore provides the evidence base necessary for a practical resilience framework ([de Bruijn et al., 2017](#)), specifically in ‘adopting a system’s approach’ and ‘remaining resilient into the future’. It also moves towards addressing stakeholder concerns about EEA, including how useful it is for policy in isolation ([Osaka and Bellamy, 2020](#)) and its lack of consideration of vulnerability and exposure ([Parker et al., 2017](#)).

### 3.1. Assessing extreme weather resulting in climate-related losses

#### 3.1.1. Hazard overviews

The inventory presents a detailed but, due to the nature of different impacts of extreme weather and our current understanding of local climate change, a partly incomplete and conditional picture of recent events. However, perfection is not necessary to add value; in spite of its caveats, the inventory is the most complete picture we have. In particular, we can assess the contributors to different hazards, including the meteorology, compounding factors and key impacts involved as well as where existing vulnerabilities may lie, what additional work is required and, critically, an overview of the anthropogenic contribution to loss and damage. Below we present a brief summary of heat waves in the UK as an example (additional examples, floods in the UK and tropical storms in Puerto Rico, are found in the appendix).

##### 3.1.1.1. Example: UK Heatwaves

**3.1.1.1.1. Summary.** In the past two decades, four major heat waves in the UK, in 2003, 2006, 2013 and 2018, are responsible for the premature deaths of an estimated 5615 (4084–7146) people, mostly in urbanised areas, in addition to travel and agricultural disruption, outbreaks of wildfires in forests and moorland and other widespread health impacts. Over 80% of the mortality occurred in 2003 and 2006, with 2234 (1936–2532) and 2323 (2008–2638) excess deaths, respectively, though there is not enough quantitative data on other impacts to compare the overall severity.

**3.1.1.1.2. Meteorological drivers.** These events are generally caused by anomalous high-pressure systems over Northern Europe, amplified by feedback from a dry and/or heavily urbanised land surface, and typically aligned with a positive summer North Atlantic Oscillation (SNAO).

**3.1.1.1.3. Anthropogenic influence.** EEA studies for the 2003, 2013 and 2018 events show that events of such magnitude were made 2–30 times more likely by ACC, depending on the event itself and the definitions used. Furthermore, the 2006 event was an extreme of comparable magnitude and a similar causal history to the others, and thus is highly likely to fall within this range. This increase in probability is in agreement with analysis of trends in both mean and extremes of heat to date, with a projected further increase in frequency and magnitude of such events in the future. Finally, an updated study of the 2003 event shows that the probability of similar events has substantially increased again in the time since it actually occurred (Christidis et al., 2015).

**3.1.1.1.4. Action taken.** The UK created a heatwave plan after the 2003 event, the implementation of which may be responsible for the significant reduction in mortality in 2013 and 2018 relative to the earlier events. In May 2018, seasonal forecasts that predicted the dry conditions to come over Northern Europe were shared with government contingency planners. However, the prediction for surface temperatures showed no significant deviation from the trend over the same region and thus underestimated the hot conditions (McCarthy et al., 2019).

**3.1.1.1.5. Existing vulnerabilities and further work.** In 2018, most of the statistically significant regional mortality rates were recorded among 65 + year olds in London, which suggests an ongoing vulnerability of those specific groups to heat extremes (Public Health England, 2019). Furthermore, in the UK Climate Change Risk Assessment (CCRA) trends in heat-related mortality and related impacts are considered but the risks from individual extreme events, particularly those without current precedent for the UK, remain largely unaccounted for (Committee on Climate Change, 2016). More work must therefore be undertaken to study the current and future risks for urban and ageing communities and to acknowledge the potentially devastating impacts of highly extreme summers in risk assessments, in addition to the overall trend.

#### 3.1.2. Direct quantification

These overviews incorporate the most substantial quantitative and qualitative impacts for each hazard, robust descriptions of changing meteorological extremes from EEA and other scientific understanding, and finally links between these that include relevant compounding factors. However, we can also use this framework to create a more explicit assessment of loss and damage related to ACC. For any event with an attribution statement, the ACC-related impacts can be approximated by multiplying the total quantifiable impacts with the best-estimate FAR value. For example, the attributable insured losses  $I_{att}$  from a flood could be approximated as  $I_{att} = I_{total} \times FAR$ , where  $I_{total}$  is the known total insured losses of the event. This approach was taken in the pathfinder report commissioned by the New Zealand treasury to approximate the fingerprint of ACC on extreme weather impacts in the country (Frame et al., 2020a) and has subsequently been applied in the context of US hurricanes (Frame et al., 2020b). This method could equally be applied to any quantified impacts from an event, including overall economic loss or mortality.

In Tables 1–3 we present estimates of attributable impacts for major events in the UK and Puerto Rico. These figures should be interpreted in the context of the uncertainties on each value, the variation in how FAR values were calculated, and that there are events with no data. In addition, this calculation only provides a first-order estimate with clear caveats. Namely, it utterly neglects non-linear effects, such as the relationship between temperature and human health, and thresholds, such as overtopping flood defences or the destruction of critical infrastructure.

**Table 1**

Estimated attributable mortality from UK heatwave events with quantitative attribution statements.

Event	FAR	Total Mortality	Attributable Mortality (Best estimate)
2003	0.5 (>0.5)	2234 (1936–2532)	1117
2018	0.5	863 (227–1499)	432

**Table 2**

Estimated attributable damages from UK flood events with quantitative attribution statements. \*Converted from GBP using conversion at the time of occurrence according to <https://www.exchangerates.org.uk/GBP-USD-spot-exchange-rates-history-2016.html> (accessed 23/09/2020).

Event	FAR	Total Damages (\$m)	Attributable Damages (Best estimate - \$m)
Autumn 2000	0.6 (0.2–0.85)	5900	3540
Summer 2007	≥0.5	8448	4224
Winter 2013/14	0.30 (–0–0.38)	1500	450
Winter 2015/16	0.37 (–0–0.6)	2176*	805.1

**Table 3**

Estimated attributable impacts from Hurricane Maria in Puerto Rico. \*FAR statement of intense rainfall related to long term climate trends.

Event	FAR	Total Damages (\$m)	Attributable Damages (\$m)	Total Mortality	Attributable Mortality (Best estimate)
Hurricane Maria, 2017	0.79* (>0.02)	68,000	53,720	4645 (793–8498)	3670

Here, the total attributable mortality on heatwaves is likely an underestimate; both FAR values quoted are thought to be underestimates and there is no FAR estimate for the destructive 2006 event, which is likely to have been amplified by ACC. Moreover, framing the attribution statement as an increased intensity and considering the non-linear health implications may yield a higher mortality fraction. By contrast, the estimate for Hurricane Maria is highly likely to be an overestimate. The FAR value is based upon an analysis of observational data of long-term climate trends, and therefore is not directly linked to ACC. Furthermore, it is a statement for the most extreme rainfall observed over part of the island and does not include wind-driven impacts.

In effect, we propose using inventories of past events to create high-level syntheses of our understanding of each hazard as well as calculating the anthropogenic influence on the total impacts. These could then feed into a comprehensive assessment of all hazard-related impacts for a given nation or region, with the current influence of ACC highlighted. Such an assessment would provide a valuable communication tool for describing and tracking the state of the climate and ongoing vulnerabilities, applicable to policy-makers and the wider public alike.

### 3.2. Exploring drivers of past impacts and informing future risk assessment

A further strength of the inventory is in providing rich case studies that can serve as probes of changing risks. In this case, inventories provide a foundation for further analysis. Here we illustrate this through two types of experiment in which actionable information is gleaned from considering how the contributing factors in past events, including hazard probability, exposure and vulnerability, are likely to evolve in different hypothetical scenarios and the implications of this for the impacts. Crucially, such experiments are flexible and can be tailored to the needs of different stakeholders. This methodology fits firmly within the ‘storyline’ framework described previously (Hazeleger et al., 2015; Shepherd, 2016). There is also an important distinction between insights naturally emergent from the inventory and those that requires further work - in this section we will provide examples illustrating both.

#### 3.2.1. Assessing future risks

Events of the recent past are, by definition, plausible. It is therefore feasible to create case studies of future weather by nesting these factual events in modified worlds (e.g. Rasmijn et al., 2018; van der Schrier et al., 2018). A trivial case could be placing past events in the context of changing exposure using a simple proxy of changing population, such as the number of people exposed to tropical storms in the Caribbean and eastern US. A more interesting experiment could integrate socioeconomic development scenarios with migration flux into cities and the associated heat island and run-off effects, plus infrastructure and adaptation changes. Then, the experienced impacts in each counterfactual scenario could be modelled, based on a factual meteorological event (e.g. Glotter and Elliott, 2016). For example, by placing the current and future exposure and vulnerability of residents of London and Paris in the context of the disastrous heatwave of 2003, the risk of heat-based mortality in the two cities in the 2020s could be assessed. Finally, by utilising climate modelling the meteorology of past events could be tweaked to align with the future climate of each development scenario, thus creating an array of future risk pathways. To continue the example above, this would involve studying the change in magnitude of a heatwave of the same return period in each city and each scenario, and modelling the added effect of this upon mortality.

Projections already exist globally for a variety of forcing scenarios (the representative concentration pathways – henceforth RCPs) and socioeconomic development scenarios (shared socioeconomic pathways – henceforth SSPs) that can provide a physically consistent basis for such work. Experiments may even consider the cost-benefit trade-off in these futures by weighing up the changing risks with other development considerations.

##### 3.2.1.1. Case study: changing mortality risk in UK heatwaves

**3.2.1.1.1. Introduction.** From the inventory we can identify that mortality in summer 2018 was triggered by short pulses of extreme heat and was particularly rife among older populations (over 65s) residing in London and other large cities. This immediately highlights an ongoing risk to a specific group of people in the present day. Here we build on this insight and undertake a simple experiment exploring how the changes in both the hazard, in terms of the probability of similar extreme heat events, and exposure, in

terms of the number of individuals in elderly urban populations, are changing over multiple policy-relevant timescales: 10 and 25 years after 2018. This will enable us to estimate the trajectory of risk assuming constant vulnerability, thus providing an evidence base for adaptation policies to reduce vulnerability accordingly (Fig. 1).

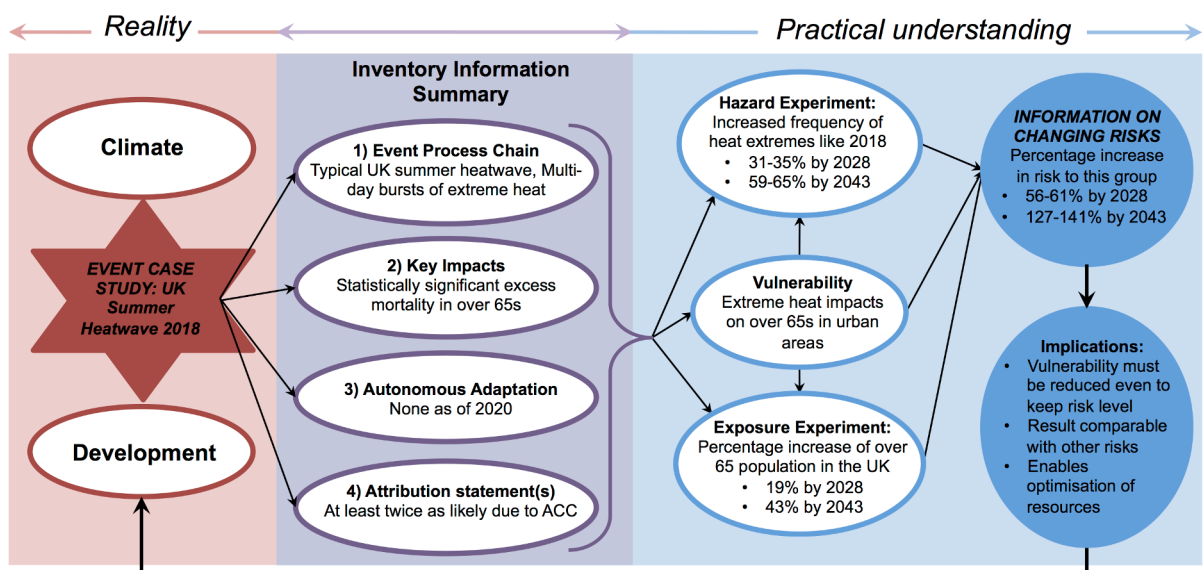
**3.2.1.1.2. Methods.** In order to assess the contribution from changing probability of extreme heat, we define an event as the annual maximum of 3-day mean of daily maximum temperature (TX3x) exceeding the observed 2018 threshold, over two spatial scales. Critically, this metric is closely linked to mortality (D’Ippoliti et al., 2010; Van Oldenborgh et al., 2019). The event magnitude at each scale was determined using the observational dataset E-OBS (Haylock et al., 2008), detrended according to globally-averaged mean surface temperature (Hansen et al., 2010) as in Leach et al. (2020). This delivered event definitions of 25.76 °C for the entire British Isles region (−10.6–2°E, 49.8–59° N), and 29.72 °C for the region centred on South East England (−2–2 °E, 50.5–53° N) - see Table 4.

We then identified the model event magnitudes corresponding to the same return periods as the observed events, using the period 2016–2020 with 16 ensemble members in the EC-Earth model (Hazeleger et al., 2012), and 2020–2022 with 100 ensemble members in Marius (Guilod et al., 2018), as only data from 2020 onwards was available. Equating the events through return periods minimised the error from model bias, assuming reasonable consistency in the bias itself. All uncertainties were estimated using a bootstrapping technique for the event magnitudes, which then corresponded with a range in return period values for a given model distribution.

For the estimates of future hazards, we focused on the changing return periods of events equivalent to that of 2018. This is the most directly applicable metric to this risk analysis, rather than studying the changing magnitudes of yet more severe events, because we know the 2018 event to be fundamentally plausible. An extension to this analysis could therefore instead focus on the changing magnitudes of constant return period events.

Alongside the hazard analysis, the changing exposure of elderly urban populations was studied using subnational population projections from the Office for National Statistics (Office for National Statistics, 2019). We calculated the fractional population growth, fractional change in the percentage of elderly people and thus the absolute fractional change in the elderly population, both in London and the wider UK (Table 4). The estimates of exposure for 2028 and 2043 were then combined with the change in probability of extreme heat events like 2018 in each model, giving estimates of the change in risk for the populations in each region.

**3.2.1.1.3. Results and discussion.** The observational data shows that the impactful event of 2018 was not unlikely at the time of occurrence, with return periods of about 4 years over the British Isles and 3 years in the hottest region over South East England. This suggests that even in the ‘present day’ climate defined in this experiment there is already a substantial risk. The magnitude of events corresponding with these return periods in the two models differ largely with each other and with observations, with EC-Earth being too cold while Marius is too hot. Nevertheless, the models show remarkable agreement in the change in return period for the event at both spatial scales and both time horizons consistent with the observations. Massey et al. (2015) and references therein did show that the dynamics of large scale temperature extremes are reasonably well represented (see also Guilod et al., 2017), which increases our confidence that future changes in return period are reliable in spite of the magnitude biases, and given the model is only compared to itself with respect to magnitude. This reasoning does however not hold for more localised heatwaves (city or county scales) where badly represented atmosphere-land feedbacks lead to an underestimation of increasing trends (Vautard et al., 2019). Consequently, using the models for the two large regions of interest there is strong evidence to expect an increase in this hazard, with 2043 return periods down to ~ 2.4 years for the British Isles event and ~ 2 years for the South east England event.



**Fig. 1.** Case study using the inventory framework using an impactful event of the recent past, the 2018 UK summer heatwave. The 2018 UK heatwave from the inventory is used to highlight a key source of ongoing vulnerability, then the risk framework is applied to this through analysis of changing hazard and exposure. Presented are the results for the entire UK region - see Table 4 for complete results.

**Table 4**

Changing hazard and exposure of vulnerable populations to 2018-like heatwaves over two spatial scales, using two different climate model ensembles alongside subnational population projections. 5–95% confidence intervals for event magnitudes and return periods are included in brackets. \*Data refers to the entire British Isles region unless otherwise specified in the table. \*\*Data refers to the entire SE England region unless otherwise specified in the table.

Region	Observational event definition – 2018 TX3x from E-OBS		Model events with same return period		Future return periods of 2018 event (years)			Population changes						Risk factor for constant vulnerability (hazard × exposure)	
	Magnitude (°C)	Return period (years)	Model	Equivalent magnitude (°C)	2018	2028	2043	Total population change factor		Factor of change in percentage of over 65 s		Total exposure change factor		2028	2043
								2028	2043	2028	2043	2028	2043		
British Isles	25.76	3.91 (5.82–2.77)	Marius	28.92 (28.15–29.63)	3.91 (4.50–3.41)	2.99 (3.35–2.68)	2.32 (2.55–2.12)	1.04 (UK)	1.09 (UK)	1.14 (UK)	1.31 (UK)	1.19 (UK)	1.43 (UK)	1.56 (UK)	2.41 (UK)
			EC-	21.27	3.91	2.89	2.46							1.61 (UK)	2.27 (UK)
			Earth	(20.96–21.54)	(5.13–3.04)	(3.96–2.22)	(3.23–1.95)								
South East England*	29.72	3.08 (4.44–2.33)	Marius	33.04 (32.21–38.50)	3.08 (3.49–2.79)	2.72 (3.04–2.49)	2.10 (2.30–1.95)	1.05 (London)	1.10 (London)	1.20 (London)	1.54 (London)	1.26 (London)	1.70 (London)	1.43 (London)	2.49 (London)
			EC-	24.13	3.08	2.22	2.07							1.75 (London)	2.53 (London)
			Earth	(23.81–24.40)	(3.88–2.51)	(2.76–1.85)	(2.53–1.74)								

∞



The subnational population data project increases in overall population and the fraction of older people, both across the entire UK and in London. This further compounds the increasing risk from the hazard itself, leading to an overall increase in heat-related mortality risk of over 50% by 2028 and up to 150% by 2043 in both regions. In the case of constant vulnerability, this indicates the potential loss of many hundreds of lives per year even in the absence of other, record-breaking heat extremes. It therefore highlights the urgency of measures to reduce vulnerability.

### 3.2.2. Black Swans and Dragon Kings

In a changing climate, the probabilities of events at the tail of the distribution generally increase most rapidly (Fischer and Knutti, 2015). Thus there is an ever-greater possibility of totally unprecedented events with no analogue in living memory. Until recently, a subclass of these events, dubbed ‘Black Swans’ (Taleb, 2007), was thought to be impossible to predict except in hindsight due to the presence of epistemic uncertainty. However, the recently proposed method of ‘downward counterfactuals’ (Woo, 2019) capitalises on the historical record, utilising stochastic simulations of past events and near misses to probe the physical plausibility of the formerly unexpected.

In essence, this methodology is a tool that pushes back the boundary of the unknowable. In doing so, it allows us to consider many (but of course not all) Black Swans as ‘Grey Swans’ or ‘Dragon Kings’ (Wheatley et al., 2017); those events without precedent that can nonetheless be understood to be feasible given the appropriate conception – in other words, those governed largely by aleatoric, or statistical, uncertainty (Paté-Cornell, 2012; Sornette, 2009). At this point the distinction between Dragon Kings and Black Swans is largely philosophical and, while this nuance is still important in terms of identifying the necessary methodology, here the key point is practical; assessing the risk of destructive and unprecedented events. Therefore, the term Black Swans will be employed for the remainder of this work to describe events that were or may yet be utterly unprecedented, whether strictly anticipatable at the time or not. Recent examples include the Russian heatwave of 2010, European heatwave of 2003, Hurricane Katrina in the US, Hurricanes Irma and Maria in Puerto Rico, and the 2010 floods in Pakistan.

To return to the inventory, studying such events could be perceived as a weakness because, by definition, unprecedented events will not be accounted for in the recent past. However, past events do provide a foundation of plausibility from which potential ‘black swans’ could be discovered and “the larger the number of notable historical events in the recorded past, the more extensive is the combined coverage of extreme events spanned by the space of downward counterfactuals” (Woo, 2019). There are two complementary perspectives through which this may be achieved.

Firstly, past catastrophes from different regions pose a warning. In 2003, Europe experienced an unprecedented heatwave that resulted in the deaths of tens of thousands. And in 2010, this occurred in Russia. And although both events, like all extremes had natural causes as well (Dole et al., 2011), they were made substantially more likely by anthropogenic climate change (Christidis et al., 2015; Otto et al., 2012; Rahmstorf and Coumou, 2011; Stott et al., 2004). Merely acknowledging its physical plausibility in a variable and warming world, in the aftermath of such an event to the west, could have motivated preparation for such an eventuality. In this case, little physical insight will be gleaned regarding the plausibility of such events due to the fundamental nature of differing climatologies and exposure and vulnerability in different regions. Nevertheless, inventories provide a basis for systematic inclusion of potential Black Swans in risk assessments, particularly highlighting where similar vulnerabilities may lie in other regions and providing ‘lessons learned’ in the aftermath of disasters. Inventories provide a foundation for this with little additional work required, enabling other nations to take factual black swan events into account in climate risk assessments in a systematic manner.

Secondly, we can ask if events of the past could have been far more devastating given slightly different, but still plausible, circumstances. For example, for an event in which a town’s flood defences narrowly held back a river, how much greater would the magnitude of rainfall have needed to be for it to have escalated from negligible impacts to highly destructive? We have already acknowledged that using an impact-based threshold eliminates most ‘near-misses’ from the inventory. Nevertheless, given some plausible perturbations to the antecedent conditions, all events may be simply ‘near-misses’ of a more destructive counterfactual version of themselves.

**3.2.2.0.1. Example: UK heatwave.** In 2003, the UK experienced the periphery of a heatwave that caused untold suffering across Europe. Though this was enough to cause the premature deaths of thousands, the UK has never experienced a truly catastrophic event such as in mainland Europe or Russia. Nevertheless, there exists some threshold at which the impacts would be amplified to these levels. This is complex, because the mortality associated with temperatures vary by region and by season. However, as with Russia, the UK has a relatively low threshold for severe impacts. In London, for example, studies show that the risk of mortality follows a sharp exponential rise with temperature (Baccini et al., 2008). It is therefore critical that the likelihood of such events, however low, are explored and an appropriate level of preparation put in place.

To do so, projection analysis of anomalous events such as these must be undertaken, with attribution studies alongside to isolate the key drivers such as ACC. Past events such as 2003 form a strong physical basis for such experimentation. For example, asking: how would events with the same return period as the 2003 event look in a warmer world? Then, what is the plausibility of a high-pressure system similar to 2003 forming slightly further north, thereby bringing more extreme temperatures to the UK and Scandinavia? Finally, how do the answers to these questions change in different climate and development scenarios?

**3.2.2.0.2. Example: Puerto Rico Hurricanes.** For Puerto Rico the twinned hazard of Hurricanes Irma and Maria was a black swan; no direct precedent existed for an event of such catastrophic impacts. However, in hindsight there was sufficient reason to anticipate such a hazard through counterfactual thinking. Even in recent memory the mainland US and other Caribbean islands experienced massive

destruction from tropical storms, while Puerto Rico itself experienced severe impacts from storms such as Jeanne in 2004 and Irene in 2011. In part, the impacts of the event may have been mitigated by additional preparedness following analysis of the risk of such an occurrence.

Now, the nature of black swan events means that we are forced to consider how it may have been even worse. The event was already compounded by the fact that Irma struck just weeks before Maria, saturating the soils of the island and degrading some infrastructure. But what if Irma had also made landfall, thereby causing further destruction and crippling resilience ahead of Maria? From historical records, model runs and physical reasoning, such as the rate of recharge of sufficient ocean heat content, is there good reason to discard the possibility of two concurrent strikes? If not, what is the probability of such a compound event occurring in the future? The occurrence of this event indicates the non-negligible plausibility of yet worse circumstances, which in turn strongly suggests the benefit of considering additional risk in rebuilding and future crisis management.

Finally, it is critical that the lessons of this event are not limited to Puerto Rico; it has implications for every island in the Caribbean as well as the eastern seaboard of the US, where, in the absence of this lesson from Puerto Rico, the concurrent strike of powerful cyclones may still be considered a black swan.

#### 4. Global policy implications

On top of the national interest, creation of inventories of the impacts of human-induced climate change across the world would be of significant interest to the broader international community. This is evident by looking through the lens of the Paris accord. In particular, inventories have the potential to aid two areas of the agreement that currently present unique challenges: adaptation (Articles 7 and 14) and loss and damage (Article 8). Additional utility could also be argued for other articles subsections, such as ‘Technology transfer’ in Article 13, though we do not explore such links here.

Article 7 sets out the global goal on adaptation of “enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change”, and goes on to develop a framework for such action. Among other aspects, this includes strengthening international cooperation in a number of ways, including “Sharing information, good practices, experiences and lessons learned”. Article 14 then introduces the global stocktake system to monitor the implementation of the agreement, stating that it shall do so “in a comprehensive and facilitative manner, considering mitigation, adaptation and the means of implementation and support, and in the light of equity and the best available science”. Taken together, this is a clear mandate for global research efforts to better understand and systematically track adaptive capacity (Tompkins et al., 2018) and for decision makers to ratchet this up in line with this evidence.

Article 8 acknowledges “the importance of averting, minimizing and addressing loss and damage associated with the adverse effects of climate change”. It proposes that nations “enhance understanding, action and support ... on a cooperative and facilitative basis with respect to loss and damage”. It further highlights key areas where work and cooperation is needed, including “Events that may involve irreversible and permanent loss and damage; Comprehensive risk assessment and management; Non-economic losses; and Resilience of communities, livelihoods and ecosystems.” Since Katowice 2018, the stocktaking process in article 14 additionally “may take into account” the loss and damage considerations from article 8, though will not explicitly take stock of loss and damage.

Despite the existence of this accord, and the explicit task to include adaptation and Loss and Damage in the global stocktake underpinning the agreement, there is still no established system for tracking adaptation and vulnerability to climate change or the associated loss and damage. This is for an array of reasons, from the perceived and very real political barriers (Boyd et al., 2017) to the disparity in data between regions and the difficulty in assessing non-economic impacts (Serdeczny, 2019).

Inventories of past events are a logical starting point to provide a foundation for this, in particular as impacts relating to extreme weather are already recorded in various ways, albeit not comprehensively (Harrington and Otto, 2020). In particular, past extremes explicitly highlight existing vulnerabilities. This is particularly pertinent in cases where rebuilding strategies in the wake of a disaster failed to reflect the risk of similar or even more destructive future events.

The proposed inventory builds on approaches that have been proposed that bypass the political and ethical questions surrounding compensation, which science alone can never answer, instead utilising attribution science in a broader pragmatic way to identify drivers of loss and damage that assist in optimising resources for minimizing risk (James et al., 2019). And it does this on a policy-relevant horizon and in collaboration with other science that considers the longer-term picture.

In Section 3 we furthermore discussed how inventories provide a transparent and bottom-up approach to understanding climate-related loss and damage from extreme weather. We clarified that, while this is distinct from a full ‘social cost of carbon’ estimate, it is complementary to the top-down approach to calculating specific loss and damage (see e.g. in Frame et al., 2020a). Though the inventory method is still limited by geographical biases in both the availability of information and prevalence of science such as attribution (Otto et al., 2020a), it is nonetheless the most complete option we have. It also highlights such biases, providing evidence for the need for a more representative distribution of analysis and research. Furthermore, inventories have capacity to handle non-economic and even purely qualitative losses, as well as facilitating the assessment of present and future risk as in Section 3. Taken together, this might be a valuable tool and evidence base to inform the Warsaw International Mechanism, specifically for the aim of “enhancing knowledge and understanding of comprehensive risk management approaches to address loss and damage”, for which there is a dedicated working group.

Alongside this, addressing present and future loss and damage is inextricably intertwined with identifying key areas for and optimising adaptation. For example, inventories provide case studies of adaptation being to some degree unsuccessful, thus contributing to the ‘experiences and lessons learned’ element that is core to international cooperation. Also, the standardised nature of the system facilitates this sharing of information across borders and helps to keep the process fair and transparent.

Our inventory system is simply a natural extension of this pragmatic approach to adaptation and loss and damage, and additionally

complements recent work e.g. by Germanwatch (Eckstein et al., 2019) that utilised hazard databases stored by reinsurance companies to calculate a global climate risk index (CRI) for every nation. The integration of EEA helps to clarify the ‘climate risk’ aspect, distinguishing the specific ‘anthropogenic climate risk’. Furthermore, inventories include more impact information, on the scale of individual regions, than the re-insurance datasets used to construct the current indices. Finally, some catastrophes could be inferred to pose a level of risk to all nations in the same region. For example, largely due to Hurricane Maria, Puerto Rico is placed at number 2 in the entire world for climate risk. However, in accordance with black swan methodology, the destructiveness of this event indicates a clear risk to all Caribbean islands and the eastern coast of the US going forwards.

We do not claim that inventories present a full solution to this challenge. The most successful adaptation measures are inherently excluded from the database as a direct result of using an impacts-based threshold (Section 2.2), while the impacts of slow-onset and irreversible events require completely separate bodies of work. Rather, inventories provide a transparent line of evidence for tracking and understanding adaptation measures for extreme weather risks on a global scale. Similarly while hazards continue to grow in a warming world we are only starting to understand our vulnerability if we record it (Harrington and Otto, 2020). The more comparable we are compiling this information the faster we can learn and understand the impacts and avoid future Loss and Damage.

## 5. Conclusions

The body of literature linking individual extreme weather events to ACC grows every year. Thus far, this has remained largely distinct from efforts to prepare for and adapt to disasters, and to take stock of the resulting loss and damage in the aftermath. Here we set out a framework for recording extreme weather events and the associated attribution work in a standardised inventory to better utilise this science in real time and at the scales risk assessments are made and adaptation is implemented. It is a pragmatic approach utilising existing data and concepts at local and national scales that bypasses interdisciplinary hurdles and addresses a clear need for such information to understand climate-related losses and identify vulnerabilities. Such a system facilitates a bottom-up approach to assessing climate risk. Studying factual events of the recent past enables us to build risk analysis around lived experience at local scales, while counterfactual analysis of historical events can help to expose plausible, more severe catastrophes. Assessing risk in this way inherently places vulnerability front and centre, thereby aiding in optimisation of resource deployment for disaster preparedness and adaptation. To evaluate and improve the practical utility of this inventory concept for a variety of stakeholders, formal feedback and development are now required. The national inventory further provides a framework to identify losses and damages as well as progress in adaptation to feed into the global stocktake requested by the Paris Agreement as well as the Sendai Framework on disaster preparedness.

## 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.

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## Appendix A

### Hazard Overviews

#### 1 UK - Floods

##### Summary:

A total of 26 flood events with significant impacts occurred in 16 of the 20 years from 2000 to 2019 in the UK. These floods resulted in a total of \$22 billion in direct damages to property and infrastructure, as measured at the times of occurrence, the direct deaths of 39 people, as well as at least £13 billion in economic disruption estimated in the 2012 events alone. Flooding in the UK occurs over a range of spatiotemporal scales, from local flash flooding over 1–2 days, such as Glasgow in 2002, Boscastle in 2004, Carlisle in 2005, Morpeth in 2008 and Cumbria in 2009, to regional inundations over several periods of a month or more, such as central England and Wales in summer 2007, Southern England in 2013/14 and Northern England and Southern Scotland in winter 2015/16. Two of the most destructive ‘individual’ events, 2007 and 2012, were extremely wet summers, but impactful events were most common in late autumn and winter overall.

##### Meteorological Drivers:

Flooding most often occurred when the jet stream was shifted over Northern Europe and strengthened, generating persistent westerlies that brought low-pressure systems over the UK that resulted in multi-day pulses of heavy precipitation, each of which was not necessarily extreme. In summer this aligned with a negative NAO, such as in 2007 and 2012, and in winter with a positive NAO, as in 2013/14 and 2015/16. It also most commonly occurred after the ground was saturated by sustained, though again not necessarily extreme, rainfall in prior months and seasons. For example, in November 2019 almost a month of rainfall fell in 24 h in a wide swathe from Sheffield to the Humber over catchments already saturated by a wet September and October, causing the rivers Derwent and Don to burst their banks.

There are several cases of more localised flash flooding resulting from intense areas of low pressure moving over the UK, though the causal factors creating severe impacts from such events on a small spatial scale were diverse and extended beyond meteorology. In Boscastle in 2004, destructive flooding was triggered by a combination of a strong convergence line along the Cornish coast and the local topography, with 3 steep sided river channels converging on the village. In Carlisle in 2005 orographic rainfall over the Lake District swelled the river Eden, which then blocked discharge from sewers and drains resulting in hydraulic overload. And in Glasgow in 2002, antiquated sewerage systems were overwhelmed by run-off from an extreme bout of rainfall over a single night.

#### Anthropogenic influence:

A total of 9 out of the 26 events recorded in the inventory have attribution statements associated, all of which are the more spatially widespread events. Of those, the only inconclusive study focused on summer rainfall extremes over a large portion of Northern Europe in 2012. All attribution statements for events in the UK in autumn and winter indicate an increased probability due to ACC and analysis of the extreme July rainfall of 2007 also showed a significant anthropogenic influence, though notably the signal was less clear for June and August.

#### Action taken:

Following the most impactful flooding events, funding for more robust defences was invariably announced. For example, Boscastle was protected by deepened river channels, a new relief culvert, a stone catcher to prevent culvert blockages and a bespoke flood warning service. In Morpeth, flood defences were announced after the 2008 event but work began only in 2013, after the town was struck by additional flooding in 2012. In Carlisle, additional defences were built and later held firm in the Cumbrian floods of 2009, an event which also resulted in improved defences being built in Keswick. However, in the extraordinary winter of 2015/16 both the new Carlisle and Keswick flood defences were overtopped. Following this very widespread and destructive event the UK government announced an extra £700 m in flooding defences, up to a total of £3 bn over 6 years. A dedicated £58 m of this additional funding was directed towards Cumbria, recognising the ongoing vulnerabilities there. Furthermore the government commissioned the 'National Flood Resilience Review' (REF) to assess the likelihood of extremes in the immediate future, and to prepare accordingly.

#### Existing vulnerabilities and further work:

The cycle of adaptation measures following impactful flood events suggests the need for a more proactive approach to assessing risks to build resilience ahead of time. This is corroborated by major flood events in late 2019 and early 2020 that affected large parts of the midlands, Yorkshire and the Humber, indicating ongoing risks. This is further reinforced by the body of attribution work on UK floods, which clearly show that anthropogenic influence is amplifying the frequency and magnitude of such events.

In light of this attribution work, the 2017 CCRA statement that "climate change may lead to increases in heavy rainfall and significantly increased risks from fluvial and surface flooding by mid-century" is inadequate. Nonetheless, the report recommends 'more ambitious' strategies for long term risk management in line with projected risk, as well as more integrated natural management solutions. Furthermore, the 2016 National Flood Resilience Review makes recommendations for the short term. This is based on extreme rainfall scenarios that show that over the decade following 2016, there may plausibly be events 20–30% more intense than already observed, with a 90% likelihood that these scenarios will not be exceeded. In combination with flood modelling, the conclusion was reached that areas at risk but still largely align with the 'Extreme Flood Outlines' defined by the Environment Agency. Positive progress is clearly being made in this sphere, with government working with industries and preparing the best available evidence for the next round of flood management funding in 2021 onwards. It is clear that the will to build greater flood resilience is present, though understanding of risk over both the short and long terms must be improved for this to be effective. Past events provide a complementary approach to projections and can provide location-specific insights over a range of timescales.

#### 2 Puerto Rico - Tropical Storms

##### Summary:

Between 2000 and 2017, Puerto Rico was struck by at least 7 impactful tropical storms. Extreme rainfall and high winds from these events caused flooding, landslides and property destruction. Notably, direct damages exceeded hundreds of millions from Storm Jeanne in 2004 and Storm Irene in 2011. In the 2017 season, the island experienced a catastrophic compound event. On 6th September, Hurricane Irma passed 50n mi to the north of the island, bringing extreme rainfall, high winds and storm surges to the north coast. This was a destructive event in its own right and caused \$750 m in damages to property and infrastructure. Then, just two weeks later, the category 4 Hurricane Maria made landfall and travelled directly over the island. Over 4500 people lost their lives, power and water supplies to all 3.4 million residents of the island were disrupted, in some cases for several months following the event, and total damages were at least \$68 bn and as high as \$95 bn.

##### Meteorological Drivers:

Like Irma and Maria, almost every tropical storm to affect Puerto Rico in recent years has undergone a similar formation process; in 72% of all NA tropical cyclones an African Easterly Wave departed the west coast of Africa (Russell et al., 2017), then typically moved westwards under the influence of a sub-tropical ridge, convection became increasingly organised and the low strengthened further, it underwent rapid intensification over a region of warm surface waters and low vertical wind shear, reached maximum intensity around the Caribbean sea and deflected increasingly northwards as the ridge weakened (see inventory).

### Anthropogenic influence:

The extreme rainfall from Hurricanes Irma and Maria was amplified by 6% and 9%, respectively, by anthropogenic forcing, though no discernible influence was found on the intensity of the storms. No other attribution studies exist for other storms that affected Puerto Rico. However, this research is reinforced by attribution analysis of the long-term trend in rainfall, finding that Maria-like rainfall was increased in likelihood by a factor of nearly 5. Additionally, the rainfall associated with other North Atlantic Hurricanes Harvey and Katrina was also amplified by ACC. More work is required to fully understand the anthropogenic influence on other such events, beginning by assessing the applicability of current attribution work to North Atlantic tropical storms more broadly and integrating this with analysis of observational trends and variability in recent decades.

### Action taken:

Prior to Maria, planning for climate-related vulnerability was focused on trends such as the threat of sea level rise to the built environment - the calamitous case of a category 4 hurricane making landfall was unaccounted for. In the aftermath of the event, some infrastructure and properties were rebuilt to withstand extreme conditions, though community-based housing groups largely led this and resources were (and remain) very limited for such expensive work. More widely, after the lack of capacity at local government level became evident, planners began taking a bottom-up approach to implementing adaptation efforts. In particular, social networks at the community level are now “viewed as foundational as resources of support, and can help spread adaptation efforts to mitigate the effects of future climate-related weather disasters” (REF). This follows lessons gained in the aftermath of the event in which community-based support and organising formed a key component of the crisis management and (albeit limited) recovery. This community-driven approach is being facilitated by the empowerment of local governments to serve as a more effective interface between the national and regional level to local municipalities, and vice versa.

### Existing vulnerabilities and further work:

Maria was so destructive partially because it was unexpected. However, with insufficient resources to equip large parts of the built environment to be more durable in the face of such extremes, a high level of vulnerability persists even though the hazard is acknowledged. Furthermore, the extreme rainfall from storms like Maria is likely to increase in future, as is the severity of storm surges due to the compounding effect of continual sea level rise. To manage the limited resources available for adaptation, accurate assessment of the risks is critical. This must involve projections of the exposure and vulnerability of the population, incorporating planned adaptation measures, as well as the probability of hazards, critically considering other ‘worst-case’ events similar to or even more destructive than Maria. The applications of this inventory for exploring such stakeholder-relevant issues are explored in the following section.

## Appendix B. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.crm.2021.100285>.

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