



When don't we need a new extreme event attribution study?

Ben Clarke¹ · Friederike Otto² · Richard Jones^{3,4}

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Abstract

The influence of anthropogenic climate change on the frequency and intensity of extreme weather events is becoming increasingly well understood. Extreme event attribution studies now exist for hundreds of events over the past few decades. However, there remain large heterogeneities in the number of attribution studies across the world and for different hazards, as well as limited capacity to conduct new studies. In this study, we suggest that there is more information to draw from past attribution studies about recent events. This is because, even though anthropogenic forcing continues to increase, many new events share meteorological characteristics with previously attributed ones. Here, we explore the possibility of using related studies and other lines of existing evidence such as projections and trend analysis to create rapid, low-resource attribution statements. To do this, we discuss the potential use cases for attribution results, including raising awareness of climate risks, preparing adaptation measures and attributing climate loss and damage. Then we discuss the considerations necessary to fulfil these uses in three cases studies, including a heatwave in the UK, a tropical storm in the Caribbean and a drought in East Africa. To conclude, we highlight the regions and hazards for which information can be drawn without new quantitative analysis, and those in which it remains urgent. This could aid prioritisation of limited resources for research into less well understood regions and hazards.

Keywords Extreme weather · Attribution · Climate change · Climate risk

1 Introduction

Anthropogenic interference in the climate system is increasingly manifesting as altered intensities and likelihoods of extreme weather events (Seneviratne et al. 2021). The science of extreme event attribution (EEA) is the toolbox used to understand and quantify these changes in intensity and likelihood of individual extreme events attributable to

✉ Ben Clarke
ben.clarke@jesus.ox.ac.uk

¹ Environmental Change Institute, University of Oxford, Oxford OX1 3QY, UK

² Grantham Institute, Imperial College London, London SW7 2AZ, UK

³ School of Geography and the Environment, University of Oxford, Oxford, UK

⁴ Met Office Hadley Centre, Exeter, UK

human-caused climate change. For any given observed event, multiple possible event definitions exist, each of which relates to slightly or significantly different aspects of the extreme; e.g. a tropical cyclone could be characterised by wind speed or associated heavy rainfall. Estimates of the influence of anthropogenic climate change (ACC) also differ depending on the event definition, including spatiotemporal factors, as illustrated in recent heatwave attribution (Leach et al. 2020) and multiple studies of rainfall from Hurricane Harvey (e.g. Van Oldenborgh et al. 2017; Emanuel 2017; Risser and Wehner 2017; Wang et al. 2018a). Similarly, the framing of the attribution study and methodological decisions also play an important role in the overall estimate of the role of climate change (Otto et al. 2016).

After more than a decade of development of this science, consensus on various best practices are beginning to emerge. For example, using multiple definitions for a given event informs understanding of the dependence of the result on this choice, as well as providing utility to a wide range of prospective stakeholders (Otto et al. 2012; Kirchmeier-Young et al. 2019; Leach et al. 2020). More broadly, the conditions required for ranking the quality of evidence provided by studies are now well established (Otto et al. 2020b) and standardised protocols are being laid out by the community (Philip et al. 2020; van Oldenborgh et al. 2021). In addition, combining quantitative approaches referenced above and narrative or storyline approaches (Shepherd 2021) can address different stakeholder needs.

As the science is further refined, its reliability and credibility grow. Moreover, our ability to attribute different extreme meteorological events increases and the cumulative number of attributed events increases every year (Herring et al. 2021; Masson-Delmotte et al. 2021). However, there is limited capacity for producing attribution studies. Relatively few resources are available and attribution studies are still produced on an ad hoc basis, with an overwhelming focus on the global north. This is for a variety of reasons including historical data availability, climate model performance and the prevalence of local experts, as set out by Otto et al. (2020a). Critically, attribution is not yet undertaken systematically in a single region of the world (Clarke et al. 2022). This not only prevents the provision of valuable information in the wake of weather-related disasters but also hinders a comprehensive overview and understanding of climate change impacts, and thus loss and damage (Stott et al. 2016; Parker et al. 2017).

By their nature, event attribution studies are tailored to specific events. However, over the course of several years in a given location, multiple events can occur that share common characteristics. For many meteorological hazards, certain synoptic circumstances are effectively a necessary precondition for occurrence. Thus, we posit that attribution studies for specific events contain far more information, about other hazards of the same type, than is currently utilised.

Even in an ideal world with sufficient capacity to undertake many studies, it may be both inefficient and unnecessary to study afresh every event that occurs. The untapped information in past studies can be combined with improved recording of hazards and impacts (Clarke et al. 2021), and ever-increasing knowledge of trends in extremes and large-scale detection and attribution studies (e.g. Seong et al. 2021). This has the potential to facilitate attribution scientists making expert judgements for very rapid, low-resource attribution statements.

Important considerations when deriving statements for new events based on past attribution studies include both how comparable different events are, and the intended use of the attribution results. First, not all events in the same region of the same type will have a comparable influence from human-caused climate change, at least not on a quantitative basis. For instance, extreme seasonal rainfall events in the UK have elicited a variety of statements: the wet summer of 2012 was not influenced significantly (Sparrow et al. 2013);

the wet winter of 2013/14 had a possible link but was ultimately inconclusive (Christidis and Stott 2015); autumn 2000 rainfall-driven floods in England and Wales and winter 2014 floods in southern England were made more likely (Pall et al. 2011; Schaller et al. 2016). This arises partly due to the seasonality itself, which plays a significant role in the link between many extremes and climate change (Stott et al. 2016), and more broadly the choice of event definition in each case (Leach et al. 2020; van Oldenborgh et al. 2021).

Second, the uses for attribution results are becoming increasingly diverse. When an extreme event occurs, a variety of stakeholders raise questions that are answered using attribution science. For example, ‘what was the role of climate change in this event?’, and ‘what are the implications for disaster risk reduction or for loss and damage from climate change?’.

In this paper, we examine when and under what circumstances some common questions can be answered rapidly based on past attribution studies and other information sources, such as projections. In particular, when can we use attribution literature to provide information to interested stakeholders? And how can we do so in a transparent manner that facilitates reproducibility?

To explore this challenge, we assess the statements that can be made for two region-specific case studies of heatwaves in the UK and tropical storms in Puerto Rico (Section 2). We then comment more generally on where and for which hazards new studies offer value, or if drawing insights from existing studies allows for sufficiently reliable conclusions on the role of climate change (Section 3). The conclusions of this study provide an assessment of where the attribution community could prioritise limited resources to add the greatest value.

2 Case studies of deriving new attribution statements

In this section, we look at two illustrative case studies, and discuss another in appendix B, to ultimately answer the following questions:

1. Under what conditions is it possible to draw useful information about a given event from past attribution studies?
2. What are the practical steps required to obtain this information?

Attribution results have a range of potential applications, each of which may value certain types of information differently. Therefore, as a precondition to answering these questions, we begin by defining what constitutes ‘useful information’ across three broad societally relevant applications: raising awareness of the risks of climate change, adapting to these risks, informing climate loss and damage. A full discussion of each of these applications surmising the minimum evidence required for each is developed in appendix A; a summary of our conclusions is presented below.

To raise awareness and connect people’s experience of extreme weather with global climate change, qualitative assessments of its role (increase/decrease/no change) are needed as well as contextual information of the weather event and its impacts including vulnerability and exposure. To inform adaptation, quantitative attribution information is preferable. While the sign of change is more useful than nothing, direct quantification, including uncertainty estimates, has far greater utility. In addition, any assessment of the role of vulnerability and exposure and if and how likelihood/intensity will continue to change with higher warming levels greatly increase the utility of attribution for adaptation. To assess loss and damage from anthropogenic climate change, a quantitative attribution statement is

needed as well as information on the role of vulnerability and exposure, and the relationship between event magnitude and impacts. For the purposes of attributing legal liability for the impacts of a given event, a dedicated study is most likely required.

In this section, we consider two case studies of extreme events with no dedicated attribution study. We begin to address the two questions through the structure of these case studies, developing the process through which we evaluate the available evidence and derive new information.

We first discuss a heatwave in the UK, for which there are several studies relating to similar events with consistent conclusions. We then consider tropical storms that impacted Puerto Rico in the recent past, for which there are several studies relating to various aspects of these complex hazards. We discuss how any event in this period may be influenced by climate change based on the existing studies. Further, in the appendix, we discuss droughts in East Africa, for which several studies give a range of messages, including a small anthropogenic signal, a lack of one, or not enough evidence to confidently determine either way.

Section 3 is dedicated to answering question 1 and includes a short summary of the case study presented in the appendix.

2.1 UK Heatwave 2006

In 2006, anticyclonic conditions dominated over Northern Europe as a ridge of high pressure persisted for several weeks, bringing clear skies and consequently high solar radiation at the surface. This was the hottest month on record over most of the UK (Prior and Beswick 2007; Perkins-Kirkpatrick et al. 2022), and of all heatwaves between 2000 and 2019 this event had the highest recorded mortality (Green et al. 2016). 2022, with its extraordinary hot and dry summer, will have probably exceeded these, though numbers are still outstanding at the time of writing (WWA 2022).

2.1.1 Relevant past studies

Other notable summer heatwaves occurred in 2003, 2013, 2018 and 2022 in the UK, each with attribution statements (Stott et al. 2004; Dong et al. 2014; Christidis et al. 2015; McCarthy et al. 2019; Leach et al. 2020; WWA 2022). In each of these cases, as in 2006, anticyclonic conditions and clear skies led to high surface temperatures. Furthermore, as in 2003 and 2013, high surface temperatures were maintained by a southerly and southeasterly airstream. This is somewhat in opposition to 2018, when anomalously high SSTs in the coastal waters surrounding the UK played a large role. In addition, in 2006, 2013 and 2018, a positive phase of the Summer North Atlantic Oscillation resulted in a northward shift of the North Atlantic storm tracks and therefore drier conditions over the UK. The ground was also especially dry in 2006 due to the prevalence of below-average rainfall for the previous two winters. As a result, the capacity of the land surface to cool through evaporation was limited and, coupled with high radiative inputs, formed a positive feedback leading to high surface temperatures (Clarke et al. 2021).

In all these recent cases, the observed temperature anomalies were higher than they would have been in the absence of anthropogenic forcing. In 2003, the temperature anomalies over Europe were utterly unprecedented and shown to have been extremely unlikely (return time of at least thousands of years) in simulations of the world as it might have been without anthropogenic climate change. Similarly unprecedented extreme temperatures (higher though as they were occurring with almost 20 more years

of rapid global warming) were reached again in 2022. In simulations of today's climate, an event like 2003 is to be expected with a probability of up to 10% in any given summer (Christidis et al. 2015) while 2022 summer temperatures are on the order of 1%. In 2013 (Dong et al. 2014) and 2018, studies showed that natural variability did play a role in the events but were insufficient to fully explain the observed temperatures (McCarthy et al. 2019).

When deciding if a new attribution study is needed, and thus when comparing attribution studies, it is important to consider whether events are within the same 'class', i.e. belonging to the same category of hazard creating the same meteorological conditions that may result in impacts (Perkins-Kirkpatrick et al. 2022). This consists of two parts. First, as above, we ensure that the events resulted from similar meteorological synoptic conditions and geographical context. Second, we check the event definitions (variable used, temporal and geographical scales) in past studies are useful in the context of the new event.

For instance, while the seminal study for the 2003 event has been updated using modern methods and modelling, and the event itself affected the UK, it has nonetheless been discounted for use here because the study does not include temperatures over the UK (Stott et al. 2004; Christidis et al. 2015). Conversely, there are numerous studies for the 2018 event that provide probability ratio (PR)—the ratio between the probabilities of event occurrence in 'factual' and 'counterfactual' (with anthropogenic forcings removed) scenarios—estimates over a range of spatiotemporal scales over the UK. For instance, Leach et al. (2020) provide three metrics for extreme heat over the UK: the annual maximum of the 90-, 10- and 1-day running mean surface air temperature (henceforth T90x, T10x and T1x, respectively). Further, while the 2013 study does not provide a direct PR to quantify the effect of climate change, it attributes the seasonal warmth event to causal factors including changes in SSTs, Arctic sea ice extent and direct warming (Dong et al. 2014).

As a final qualification, we use the methodology of Otto et al. (2020b) to rate the quality of evidence provided by the attribution studies utilised here, and find that both Leach et al. (2020) and Dong et al. (2014) are of at least 'medium quality'.

2.1.2 Deriving useful attribution statements

Direction of change It is clear that recent (2003 onwards) UK summer heatwaves have increased in frequency and magnitude due to climate change. Since most attribution studies apply to classes of events, and there is substantial evidence to suggest that the 2006 event was part of the class attributed by previous studies, as defined by its causal history, including seasonality, synoptic conditions and region, and the event definitions used, it is trivial to conclude that this statement applies to this event.

Other analyses reinforce this conclusion. In 2007, the IPCC stated that it was more likely than not that climate change had increased the risk of heatwaves (IPCC 2007). Trend analysis shows that short heat extremes in Northern Europe warmed by roughly 0.33 °C per decade, or 2.3 °C in total from 1950 to 2018 (Lorenz et al. 2019). Therefore, despite this event having occurred at a lower level of anthropogenic forcing than 2 out of the 3 available attribution studies, it was clearly made more likely and intense by climate change. Alone, this is a useful statement for raising awareness of climate impacts.

Quantification To make quantitative estimates, we consider the event definitions used in each of the past studies: on a seasonal scale, 2018 was more extreme than 2006, suggesting

that the T90x value for 2006 has a lower PR; in contrast, July 2006 remains the hottest July since records began; it was hotter than July 2018, both overall and in the hottest single days and short multi-day bursts (Cornes et al. 2018; Hollis et al. 2019) and hotter than 2022 despite the extraordinary heat observed in 2022. As such, the values of T10x and T1x in 2006 were more extreme than 2018 by at least 1 °C each, suggesting higher PR values.

PR values from 2018 are likely to be overestimates for a given similar-magnitude event from 2006 because anthropogenic forcing has continued to grow significantly in the 12 years between these events (Christidis et al. 2015; Diffenbaugh 2020). Further, the models used for the 2018 estimates display lower variability than the observations (Leach et al. 2020).

Taking these factors together, we conclude that the maximum probable seasonal value for 2018 forms an upper bound for 2006, which we can be highly confident of, thus giving a final range of possible values of $1 < \text{PRT90x} < 84$. We cannot pin down this PR with any additional confidence, but the seasonal extreme of 2006 was the least remarkable of the three statistics considered here.

For the 1- and 10-day events, the two key factors for deriving the attribution statement—relative event magnitude and anthropogenic forcing level—act in opposition on our estimate of PRs for 2006 relative to 2018. However, the largest attributable fractions occur for the most extreme events (Fischer and Knutti 2015). In all likelihood, the greater magnitudes of the 2006 event more than offsets the anthropogenic forcing discrepancy, assuming no drastic shift in the shape of the distribution of extremes (Christidis et al. 2015), suggesting that the 2006 PRs are larger than for 2018. Thus, for the purposes of making a concrete statement, the lower bounds of the 2018 uncertainty ranges form conservative estimates for the best guess at the 2006 PRs. We therefore confidently conclude that the 2006 PRs obey the following: $\text{PRT1x} \geq 2.9$, $\text{PRT10x} \geq 3.2$ (Leach et al. 2020).

These estimates form a basis for adaptation and estimating loss and damage when combined with the impacts of this event, in particular that 2689 (2229–3149) people died (Green et al. 2016; Clarke et al. 2021). None of the studies provide estimates of changing magnitude due to global warming, which makes it challenging to relate the lived experience of elevated temperatures with the attribution statements available; the only possible messages are that ‘events like this one will occur at least 3 times more often’, and ‘this event was hotter than it would have been without climate change’, with further reference to the impacts. Further information on exposure and vulnerability drivers of the impacts would supplement all of these applications. In addition, adaptation also requires deeper understanding of future changes in the hazard.

Future changes and/or trajectory None of the attribution studies considered attempt to project future changes in hazard probability due to continued greenhouse gas emissions. Nonetheless, there are two ways to build a clearer picture. First, there is no reason to believe that the trajectory presented by the attribution studies will not continue to hold. Thermodynamic arguments suggest that event magnitudes will increase at an accelerating rate with additional warming, while little evidence exists to show that dynamic changes in event formation are occurring (Mitchell et al. 2016). It is therefore reasonable to conclude that the derived attributable increases will continue to grow at least at the same rate with warming.

Second, we can use projection analysis to check this claim. The UKCP18 projections show that average daytime summer temperatures will increase by 0.57 to 0.78 °C per decade in major UK cities, under the RCP8.5 warming scenario (Eunice Lo et al. 2020). Clarke et al. (2021) project that the chance of heatwaves at least as extreme as the 2018 event will

increase over both the British Isles and Southeast England, under different warming pathways and time horizons. Since changes in probability are higher for more extreme events, it is likely that T1x and T10x conditions seen in 2006 will grow at a rate at least as fast as those seen in 2018. Over Northern Europe at 1.5 °C global warming, CMIP6 projections show an increase of 0.5 °C in annual daily maximum temperatures compared to the modern level (of approximately 1 °C); at 2 °C global warming, the difference is an additional 1.5 °C, suggesting an acceleration of hot extremes (Masson-Delmotte et al. 2021).

Vulnerability and exposure context During the 2006 heatwave, over 86% of mortality was in people over 65 years of age (Green et al. 2016), indicating a clear vulnerability of older people to heat-related health impacts. This was similar to 2003, in which 88% of deaths were from this age group (Green et al. 2016), and 2018 in which over 65 s in urban areas were significantly impacted (Clarke et al. 2021). Since 2004, Public Health England has released a heatwave plan annually, featuring a tiered warning and communication system, and preparatory measures for national, local and health authorities (Williams et al. 2019). In 2006, daily mortality was slightly lower than that in 2003 (Green et al. 2016), possibly as a result of these new measures. A major overhaul of the heatwave plan in 2012 and subsequently severely reduced mortality in the 2013 heatwave (Green et al. 2016) may also indicate the effectiveness of these existing adaptation measures.

Nonetheless, significant mortality in 2018 suggests ongoing vulnerabilities to extreme heat. Moving forward, this will be further compounded by increases in the frequency and magnitude of this hazard, and exposure to it, which continues to rise due to an ageing population, urbanisation and migration to cities (Williams et al. 2019; Eunice Lo et al. 2020; Clarke et al. 2021).

Across several major European cities including London, higher mean temperatures are associated with a greater-than-linear rise in mortality (Baccini et al. 2008; Gasparri et al. 2015; de' Donato et al. 2015; Mitchell et al. 2016; Vicedo-Cabrera et al. 2019). This effect has already been observed and is projected to rise further across England and Wales, with the strongest rate of increase in mortality for more extreme temperatures (Huang et al. 2022).

Perkins-Kirkpatrick et al. (2022) show that approximately 17% of mortality on a single July day was attributable to anthropogenic influence (due to the change in magnitude of a 1-in-4 year event). Extrapolating this over the estimate for all heatwave-related mortality for 2006 gives an estimated attributable mortality of 395 deaths. Mitchell et al. (2016) show very similar results for the 2003 heatwave, with ~20% of mortality in London directly attributable. The mortality rate in 2003 across London was ~4.5 per 100,000 people, which is remarkably similar to the wider event across the entire UK, with mortality of ~3.8 per 100,000 people. This increases our confidence in the above estimate for overall 2006 mortality.

In summary, this case study shows that it is possible to rely on past attribution studies to derive new information; see appendix C for a full summary of the derived results.

2.2 Tropical storms in Puerto Rico

As recorded in the disaster database EMDAT (EMDAT 2019) and in Clarke et al. (2021), 10 tropical cyclones substantially impacted Puerto Rico from 2000 to 2019, all between June and December. Irma and Maria, the two most impactful, occurred

within a 2-week period in September 2017. Irma tracked around 90 km north of the island, bringing high winds, storm surges leading to inundations of 30–60 cm along coastal regions, and extreme rainfall totalling 25–45 cm in some elevated locations. This led to widespread disruption to electricity and water lines as well as the collapse of some weaker structures. Before the island fully recovered, Maria made landfall as a category 4 storm. The resulting rainfall was the highest from any storm and the most intense single rainfall event, both since 1956, with over 1.5 m over 48 h in some areas. Coupled with extreme storm surge and winds at the high end of category 4, this led to thousands of deaths, tens of thousands of landslides that blocked roads, the destruction of 70,000 homes with a quarter of a million damaged, island-wide loss of power transmission and distribution infrastructure and water supplies that affected all 3.4 million residents, as well as disruption to other key medical services (Kwasinski et al. 2019; Clarke et al. 2021). The loss of services, mental health impacts and heavy net migration away from the island were sustained for months to years afterwards. Combined, these two events caused damages of at least US\$ 90B, the overwhelming majority of which came from Maria (Pasch et al. 2017). Two of the other storms, Jeanne in 2004 and Irene in 2011, caused US\$ 750 M in damages and the latter affected over a million people, while very little quantitative impact data is recorded for the other events (Clarke et al. 2021).

2.2.1 Relevant past studies

Of the 10 tropical cyclones to affect Puerto Rico, only Irma and Maria are the subjects of attribution studies. One found that ACC substantially increased the rainfall totals from Hurricanes Katrina, Irma and Maria in an area $1.5^\circ \times 1.5^\circ$ about the centre by 4, 6 and 9%, respectively (Patricola and Wehner 2018). However, no human influence on hurricane intensity was discerned. Another study analysed rainfall observations and found a significant increase (best estimate factor 4.85) in the probability of Maria-like extreme rainfall over the most affected parts of Puerto Rico, due to long-term climate trends (Keellings and Hernández Ayala 2019).

Events that affect Puerto Rico are also a subset of events that occur in the wider North Atlantic region, such as major Hurricanes Harvey, Florence, Dorian and Sandy, which have all elicited attribution study (Van Oldenborgh et al. 2017; Trenberth et al. 2018; Reed et al. 2020, 2021; Strauss et al. 2021). For Harvey, a probabilistic study of extreme rainfall from the event concluded that ACC increased the probability of the rainfall totals observed over Texas by a factor of 3 (1.5–5), or that, equivalently, the rainfall totals themselves were increased by approximately 20% (15–38%) (Van Oldenborgh et al. 2017; Risser and Wehner 2017; Wang et al. 2018b). Other work posits that the observed rainfall simply could not have occurred in the absence of ACC (Trenberth et al. 2018).

Total overland rainfall from Hurricanes Florence and Dorian were increased by 4.9% (0.3–9.5%) and 7% (5–10%), respectively, by anthropogenic influence (Reed et al. 2020, 2021). The intensity of Sandy was not influenced significantly by climate change (Lackmann 2015), but the extent of the floods resulting from storm surges was increased due to sea level rise. The ensuing damages totalled an additional \$8.1B (\$4.7B–\$14.0B) and affected 71 (41–131) thousand more people due to anthropogenic sea level rise (Strauss et al. 2021), and such occurrences will increase in frequency with further warming (Sweet et al. 2013).

2.2.2 Deriving useful attribution statements

Direction of change In the North Atlantic basin, there are several studies that show clear anthropogenic influence on extreme rainfall totals and storm surge height from tropical cyclones (Van Oldenborgh et al. 2017; Trenberth et al. 2018; Reed et al. 2020, 2021; Strauss et al. 2021; Patricola and Wehner 2018). These appear to be largely due to the influence of increased atmospheric moisture content described by the Clausius-Clapeyron relation, sea level rise and extreme ocean heat content. To determine how applicable these conclusions are to other events, we must first consider the degree to which other events are similar.

Almost every tropical storm to affect Puerto Rico in recent years, including Irma and Maria, has undergone a similar formation process: in 80% of events to affect Puerto Rico from 2000 to 2019, as in 72% of all NA tropical cyclones between 1995 and 2015, an African Easterly Wave (AEW)—a low-pressure disturbance associated with the African Easterly Jet—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, and 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 (Clarke et al. 2021). The remaining ~20% of cyclogenesis in the basin is triggered by other low-pressure disturbances, or ‘seedlings’, throughout the basin, which go through a very similar subsequent development process. Patricola et al. (2018) show that occurrence of tropical cyclones is largely independent of changes in AEW occurrence, suggesting that attribution statements are applicable across events with different seedlings.

Trend analysis adds another line of evidence. In the North Atlantic basin, there has been an observed increase in measures of aggregated cyclone activity, such as the ‘Power Dissipation Index’ and the ‘Accumulated Cyclone Energy’ (Emanuel 2005; Holland and Webster 2007; Walsh et al. 2016) but not normalised damages (Weinkle et al. 2018) and mixed results for occurrence frequency (Landsea 2007; Murakami et al. 2020) since 1970. These trends are difficult to attribute to ACC due to the high multi-decadal variability exhibited in the NA basin (Walsh et al. 2016) and changing coastal exposure and vulnerability, though a fraction of recent historical damages in the USA from tropical cyclones have now been attributed to ACC (Estrada et al. 2015).

Even though we cannot make a generalisation of anthropogenic influence on Atlantic tropical storm hazards overall, we can do so for specific aspects including extreme rainfall and storm surges—these aspects of all recent north Atlantic hurricanes were amplified by ACC. Based on the evidence above, we conclude that for any North Atlantic hurricane the extreme rainfall totals were made higher and that storm surges reached further inland due to anthropogenic warming. Hurricane Katrina in 2005 is the earliest event for which an attribution statement is available; thus, we suggest that the above statement is reasonable for events from roughly 2000 onwards, as it represents a time period of comparable anthropogenic forcing. Though the signal may have emerged earlier, such as for Hurricane Georges in 1998, there is no evidence either way for this. Overall, this retrospective attribution of events is equivalent to attributing additional events as they occur, and has important ramifications for the communication of the influence of climate change.

Quantification The conclusion above can be written as $PR > 1$ for the rainfall totals of each event that affected Puerto Rico this century. More detailed probabilistic attribution statements were estimated for the rainfall of Harvey and Maria. For Harvey, comprehensive

attribution analysis that utilised a range of methodologies, including counterfactual dynamical modelling, showed a probability ratio of 3 (1.5–5) for such extreme precipitation. Further, observation-based analysis for the most extreme precipitation totals within the two storms returned probability ratios of 9.6 (3.5+) for Harvey and 4.85 (~1–~12) for Maria. Maria was the most intense storm to affect Puerto Rico, and thus has the greatest probability ratio within a probabilistic framework. Since it is also one of the most recent, we can assume that all other events in this period likely obey the following relation: $1 < PR < \sim 12$. Based on the limited number of estimates, we cannot improve on this very broad probabilistic estimate for other storms, and we advocate caution when estimates are based off such a limited number of studies. However, attribution studies for tropical storm rainfall tend to focus more on magnitudes. This may be within the same probabilistic framework as a frequency estimate (e.g. Van Oldenborgh et al. 2017), or may be a conditional statement of magnitude change assuming that the dynamical drivers of an event occur (e.g. Patricola and Wehner 2018). In the latter case, while this sacrifices our ability to attribute the overall influence of climate change, it also vastly reduces the noise of dynamical variability and the deep uncertainties on these changing drivers, and thus enables greater confidence (Shepherd 2016).

From those studies, it is clear that rainfall intensities have been increased by roughly a Clausius-Clapeyron scaling factor of $\sim 7\%/^{\circ}\text{C}$, with a probable range of 4–9%. Hurricane Harvey was an exceptional case with magnitudes of 15–38% greater than the counterfactual event and far beyond Clausius-Clapeyron scaling. Harvey stalled over Houston due to blocking by high pressure, while record ocean heat content in the Gulf of Mexico continued to fuel the storm, potentially providing higher moisture flux through both moisture content and circulation velocities (Van Oldenborgh et al. 2017; Risser and Wehner 2017; Trenberth et al. 2018).

Harvey may be the canary in the coal mine for tropical storms making landfall on the US coast, or even across the North Atlantic region. Preliminary evidence suggests that probability ratios for extreme rainfall across the southeast US coast are very consistent across specific event magnitudes (Risser and Wehner 2017). Meanwhile, while trends in translation speeds for tropical cyclones globally are highly uncertain, limited evidence points to a slowdown across the contiguous USA (Kossin 2018; Hall and Kossin 2019). For severely affected small developing islands such as Puerto Rico and the wider Caribbean, while individual events such as Dorian have exhibited stalling behaviour, there is currently no evidence to suggest a similar trend exists (Vosper et al. 2020).

Overall, we can conclude that for tropical cyclones that affect Puerto Rico (and the wider region), it is likely that the most extreme rainfall has become up to an order of magnitude more likely, and, equivalently, is amplified in intensity by at least Clausius-Clapeyron scaling.

Future changes and/or trajectory A number of studies project future magnitude changes from tropical cyclones. A significant uptick in Harvey-like storm intensity and frequency in southeast Texas is projected by mid-century (Wang et al. 2018b), and by 2081–2100 the annual probability of Harvey-like rainfall over Texas is expected to be $\sim 18\%$ under an RCP8.5 scenario, up from 1% in 1981–2000 (Emanuel 2017). Across the Caribbean, the fraction of stalling hurricanes is not projected to significantly increase at 1.5°C or 2°C global warming, but the probability of extreme hurricanes increases significantly across most of the region. In Puerto Rico, for example, the return period of a Maria-like event decreases from 115 years in the present

climate to 75 years at 1.5 °C and 43 years at 2 °C (Vosper et al. 2020). Furthermore, by 2100, under RCP4.5, 6.0 and 8.5, Maria-like rainfall events are projected to become 21.8%, 23.4% and 36.9% more intense than the historical event, respectively. For Katrina and Irma, increases vary from 7.1 to 16.5% and 17.5 to 27.8% across the same set of projections (Patricola and Wehner 2018). There is also evidence to suggest significant increases in wind speed intensity; in 2100, wind speeds from storms like Katrina, Irma and Maria will be 6.0–13.8 knots faster, depending on the RCP scenario (Patricola and Wehner 2018).

Projected future changes in hurricane frequency from both GCMs and downscaled models also vary (Emanuel 2013; Trenberth et al. 2018), point to a slight decrease in frequency, with a larger fraction of the most intense storms (category 3–5 on the Saffir-Simpson scale) (Sobel et al. 2016; Seneviratne et al. 2021). The latter forecast is of the utmost importance, given that the overwhelming majority of damages are due to these super-storms (Weinkle et al. 2018; Clarke et al. 2021).

To conclude, it is very likely that rainfall from present and future tropical cyclones will be amplified by at minimum the Clausius-Clapeyron scaling factor, and thus at the upper end or greater than the derived range from 2000 to 2019. Across different RCP scenarios, the variation in future rainfall intensity increases by approximately 10–15%. Furthermore, storm surge heights are increasing non-linearly with warming as sea levels rise, and an anthropogenic influence on wind speeds emerges. Compound flooding hazards will thus be influenced by multiple nonlinear factors (Masson-Delmotte et al. 2021).

Without further attribution study of specific, more localised hazards, this provides a foundation for adaptation planning. However, hazards translate into impacts only where people and property are exposed and vulnerable, which has been highlighted by a number of recent events.

Vulnerability and exposure context Maria was the costliest hurricane ever recorded on Puerto Rico by at least an order of magnitude, the second being Georges in 1998 (Pasch et al. 2017). The event therefore most clearly highlights existing, ongoing vulnerability and exposure on the island. Increasingly, Maria is becoming understood as an ‘unnatural disaster’, being ‘directly shaped by existing socioeconomic and racial inequalities’ (García-López 2018), linked to extractivism, economic recession and austerity, and forced migration, and having the greatest impacts on those in poverty, in isolated communities and infirm and disabled (Lloréns 2018; Weiss et al. 2018).

A combination of sustained high winds and extreme rainfall, which triggered mudslides and flooding, led to disruption of power and water services to all 3.4 million residents of the island (Keellings and Hernández Ayala 2019). Unprecedented river flooding affected the northern side of the island, especially from the La Plata river, while the southeast, east and northwest suffered severe damage due to wave action and storm surge, affecting marinas, harbours, and coastal buildings, homes and roads (Pasch et al. 2017). The loss of critical infrastructure on an island-wide scale led to cascading impacts on health, through shortages of basic supplies, exposure to vector-borne diseases, high heat and humidity, loss of jobs and school closures (Ferré et al. 2019), as well as disruption to services including care and medication (Niles and Contreras 2019).

Poverty was (and remains) rife in Puerto Rico, with approximately 45% of the population below the federal poverty level, compared with an average of 15% across the USA, and this had a significant bearing on the magnitude and distribution of the impacts of the event (Niles and Contreras 2019). Severe damage to homes

disproportionately affected renters, low-income households and especially low-income renters, with the implication that minimum structural standards were insufficient to withstand such an event (Ma and Smith 2020). Further, health issues—both physical and mental—in the wake of the disaster occurred disproportionately more amongst the economically disadvantaged, as well as older and younger people, those living in more isolated areas and those with chronic health conditions and disabilities (Morris et al. 2018; Ferré et al. 2019; Niles and Contreras 2019; Scaramutti et al. 2019; Orengo-Aguayo et al. 2019). This was compounded by historical underfunding of health services and welfare on the island, though outreach work by healthcare workers operating at a community scale helped to meet people's urgent needs (Morris et al. 2018; Niles and Contreras 2019).

The impacts of and responses to Maria in Puerto Rico have been contrasted with those in Cuba after the landfall of Hurricane Irma, an event of comparable meteorological magnitude in these locations, respectively (Clarke et al. 2022). The most striking difference was in the long-term impacts, which were far lower in Cuba due to evidence-based risk planning that engaged with the public, and a swift and effective response that minimised disruption (Zakrison et al. 2020). In contrast, in Puerto Rico, planning for climate vulnerabilities did not account for landfall by a category 4 hurricane, while the federal aid response to Maria was widely viewed as insufficient (Walsh-Russo 2018).

Last, it is informative to consider adaptation put in place since the event transpired. At a community level, housing groups are building more resilient and extreme weather-resistant infrastructure such as storm-safe roofs, though this is expensive and capacity is still limited compared to the scale of the adaptive transformations required (Walsh-Russo 2018). In terms of planning for future disasters, planners such as the Puerto Rican Climate Change Council are shifting from a 'top-down' approach used prior to Maria towards a more 'bottom-up' approach. In other words, local communities will drive the adaptation strategies of local government, while communication channels between national/regional and local government are also being improved (Walsh-Russo 2018).

As for heatwaves in the UK, this case study shows that it is possible to rely on past attribution studies to derive new information; see appendix C for a full summary of the derived results.

2.3 Drought in East Africa

A final case study for deriving attribution statements is presented in appendix B: a drought in East Africa. Here, many studies exist for recent drought events with varied conclusions. High spatial and temporal variability in climate signals, as well as extreme exposure and vulnerability to drought hazards, means that anthropogenic forcing is currently largely negligible for droughts in the region, on average, and highly dependent on event definition. This is inherently useful, because it illustrates that a dedicated study is required in a given case for many purposes, and that the priority for the region to minimise impacts likely involves improving poverty rates and risk governance such as through early warning systems. As a result, this provides a contrasting case study in which we cannot rely solely on past studies to satisfy all requirements, but they still offer useful information.

3 Discussion and conclusions

3.1 Further considerations

Throughout the above case studies, the limitations of applying evidence across events largely arise due to the similarities of the event characteristics and the strength of the evidence itself. However, there are two cases in which even a robust pre-existing body of attribution evidence may require additional caution when deriving new statements or, equivalently, cases in which a new study would add great value. First, as the anthropogenic forcing increases, attribution statements will become outdated. This is partly addressed through our analysis in Section 2.1.2, in which the relative anthropogenic forcing at the time of occurrence is a key factor. However, as a broader comment on the body of available evidence, it would be useful for the community to provide an updated study in the region at global warming level milestones such as 1.5 and 2 degrees; while scientifically arbitrary, these provide a useful trajectory of change in risk.

Second, in the event of completely unprecedented events, past estimates may be considered too different for comparison. Nonetheless, they provide a lower bound estimate where the physical characteristics of the two events are comparable. Additionally, in many cases, past events provide examples of ‘near-misses’ of far worse events (Woo 2019; Clarke et al. 2021); for instance, if some of the physical processes are similar but some non-linear interaction of compounding phenomena resulted in the unprecedented impacts, then a partial attribution may still be plausible. This could also be allayed by an effort of the community towards multivariate and impact-focused attribution of compound events (Zscheischler and Lehner 2022).

3.2 Conclusions

Using the case studies above and in consideration of the wider literature, we can derive general answers to the first question posed: Under what conditions is it possible to draw useful information about a given event from past attribution studies? Our answers take the form of three categories within the region-hazard matrix in which broadly similar conditions apply: (i) we are confident of using past studies for most purposes; (ii) we may require a new study depending on the question(s) being asked; (iii) more studies are urgently needed. We refrain from proposing strict thresholds of evidence to define each category. In particular, any answer to this question inherently contains an element of expert judgement, and therefore a bias towards the expert’s own knowledge and interpretations. Similarly, the evidence required by two different end users could be completely different even for the same purpose. Here, to explain our own categorisation of events, we simply set out the conditions that create greater confidence in the derived statements and the evidence it is based on; namely, the event attribution literature and the regional attribution of similar hazards undertaken by the IPCC. Despite these efforts, subjectivity inevitably underlies our own conclusions, and is a cautionary note for applying this method to new events.

In the first category, which includes heatwaves in the UK and tropical storms in the North Atlantic basin, we can confidently estimate quantitative statements about the change in likelihood and magnitude for a new event. There is greater confidence in this process when there are several studies for similar hazards in a region, when studies use multiple models and event definitions, when they come to similar conclusions, and the studied

events share similar synoptic characteristics. Nonetheless, even a single study is useful, especially where multiple event definitions are employed, because (probabilistic) event attribution studies distributions of events, and because analysis of other trends or patterns in extremes can also be used to assess any derived result. Conducting this process for a new event can be used to inform the public about the probable influence of climate change without a new study.

Furthermore, derived attribution results can be extended for other uses, such as informing adaptation and adding a further line of evidence towards inferring climate-related loss and damage. First, future risks can be inferred when attribution studies provide estimates of changing likelihoods across multiple emission pathways, and/or by combining present day attribution studies with physical reasoning and projections, such as changes in extremes statistics. Second, contextualising any derived results using knowledge of the impacts of past events, and changes in vulnerability and exposure in the affected region, highlights the key drivers of impacts and thus opportunities for effective responsive action. Finally, climate-related loss and damage can be inferred through understanding the relationship between the particular magnitude of the event and the impacts.

The hazards for which this is most likely applicable are extreme heat and cold worldwide; extreme precipitation in northern Europe and central North America; tropical storm rainfall and storm surges in the North Atlantic; agricultural and other largely temperature-driven drought in western North America and Europe; and fire weather in Australia and western North America. Within the overall matrix of hazards by region, those listed above correspond to the level of evidence and consistency in signal of the case studies set out here. Both this and the statements below are based on evidence synthesised within AR6 of the IPCC and a recent topical review (Clarke et al. 2022; Seneviratne et al. 2021).

The second category contains cases in which new attribution studies may be required depending heavily on the question being asked, such as for all forms of drought in East Africa. This is the case when there are a range of studies, but it is not possible to derive an attribution statement for a new event because of mixed or inconclusive statements from these existing studies, or there are a limited number of studies. This may be due to a range of factors including data limitations, high complexity of the hazard (e.g. drought), heavy dependence on event definition, non-climatic factors driving impacts, and high natural intra-regional and temporal variability. In this case, a bespoke study is required for the purpose of informing people of any quantitative influence of climate change in a specific location. That is also the only way to infer whether and how much loss and damage may be considered climate-related.

However, it is still often possible to derive useful information for adaptation purposes. This is an emergent property of having produced several attribution studies for a hazard in one region, because they inherently raise the question ‘what is driving the risk?’, and shed light on the relative significance of climate change as a driver. For instance, results are largely inconclusive for the climate change influence in East Africa and even those studies showing a positive influence are very minor; any event in the immediate future is very likely to be similar. Knowing a likely order of magnitude change, combined with knowledge of the actual impacts and how non-climate drivers are changing, it becomes clearer where interventions will be most effective. Further, even if attribution studies show little signal in the present day, they can also look forward in time to assess when climate change may play a major role in such events (e.g. Philip et al. 2019), or at the very least may suggest insightful ways of investigating this.

This set of conditions, in which the need for an attribution study is most heavily dependent on the question being asked, is most likely to include extreme precipitation in much

of the world including most of Asia, Europe and North America, southern Africa, eastern Australia and New Zealand; as well as for tropical storm rainfall in the western Pacific; storm surges in South East Asia; all forms of drought in East Africa, China, South America, South Africa and central North America; and fire weather in southern China (Clarke et al. 2022; Seneviratne et al. 2021).

The third and final category includes hazard-region combinations in which we urgently need more attribution studies that follow modern best practices (van Oldenborgh et al. 2021) if we want to answer any queries about anthropogenic influence. As pointed out in the introduction, identifying this category is an equivalent answer to the question posed by this paper, and in general consists of those areas in which there are either no attribution studies, or the few that exist are largely inconclusive and the correspond regional trends in extremes are weak. This includes extreme precipitation in most of Africa and South and Central America; tropical storms for most basins in the Indian and Pacific oceans; and storm surges, drought and wildfires worldwide, especially South America, Asia and Africa (Clarke et al. 2022; Seneviratne et al. 2021).

Using the methodology explored in this paper, it is possible to utilise the information we have more effectively to devote more time and resources to understudied regions (i.e. those in category 3), rather than producing studies that are unlikely to add much further information because the answer is already fairly well understood. Further, attribution coverage could also be improved by standardising the recording of extreme events and their impacts, to ensure that attention is focused on the greatest sources of impacts around the world.

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Declarations

Competing interests The authors declare no competing interests.

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References

Baccini M, Biggeri A, Accetta G et al (2008) Heat effects on mortality in 15 European cities. *Epidemiology*. <https://doi.org/10.1097/EDE.0b013e318176bfcd>

- Christidis N, Jones GS, Stott PA (2015) Dramatically increasing chance of extremely hot summers since the 2003 European heatwave. *Nat Clim Chang*. <https://doi.org/10.1038/nclimate2468>
- Christidis N, Stott PA (2015) Extreme rainfall in the United Kingdom during winter 2013/14 the role of atmospheric circulation and climate change. *Bull. Am. Meteorol Soc*.
- Clarke B, Otto F, Stuart-Smith R, Harrington L (2022) Extreme weather impacts of climate change: an attribution perspective. *Environ Res Clim* 1:012001. <https://doi.org/10.1088/2752-5295/AC6E7D>
- Clarke BJ, E. L. Otto F, Jones RG (2021) Inventories of extreme weather events and impacts implications for loss and damage from and adaptation to climate extremes *Clim Risk Manag* 32 100285 <https://doi.org/10.1016/j.crm.2021.100285>
- Cornes RC, van der Schrier G, van den Besselaar EJM, Jones PD (2018) An ensemble version of the E-OBS temperature and precipitation data sets. *J Geophys Res Atmos* 123:9391–9409. <https://doi.org/10.1029/2017JD028200>
- de' Donato FK, Leone M, Scortichini M, et al (2015) Changes in the effect of heat on mortality in the last 20 years in nine European cities Results from the PHASE Project. *Int J Environ Res Public Heal* 12:15567–15583. <https://doi.org/10.3390/IJERPH121215006>
- Diffenbaugh NS (2020) Verification of extreme event attribution: using out-of-sample observations to assess changes in probabilities of unprecedented events. *Sci Adv*. <https://doi.org/10.1126/sciadv.aay2368>
- Dong B, Sutton R, Shaffrey L (2014) The 2013 hot, dry summer in Western Europe [in “Explaining Extremes of 2013 from a Climate Perspective”]. *Bull Am Meteorol Soc*. <https://doi.org/10.1175/1520-0477-95.9.S1.1>
- Emanuel K (2017) Assessing the present and future probability of Hurricane Harvey’s rainfall. *Proc Natl Acad Sci* 114:12681–12684. <https://doi.org/10.1073/PNAS.1716222114>
- Emanuel K (2005) Increasing destructiveness of tropical cyclones over the past 30 years. *Nat* 4367051(436):686–688. <https://doi.org/10.1038/nature03906>
- Emanuel KA (2013) Downscaling CMIP5 climate models shows increased tropical cyclone activity over the 21st century. *Proc Natl Acad Sci U S A* 110:12219–12224. <https://doi.org/10.1073/PNAS.1301293110/ASSET/164687B6-4B35-481B-ABF8-8B8723C38A7B/ASSETS/GRAPHIC/PNAS.1301293110I1.GIF>
- EMDAT (2019) The Emergency Events Database. Univ. Cathol. Louvain - CRED, D. Guha-Sapir
- Estrada F, Botzen WJW (2015) Tol RSJ (2015) Economic losses from US hurricanes consistent with an influence from climate change. *Nat Geosci* 8(8):880–884. <https://doi.org/10.1038/ngeo2560>
- Eunice Lo YT, Mitchell DM, Bohnstengel SI et al (2020) U.K. Climate Projections: Summer Daytime and Nighttime Urban Heat Island Changes in England’s Major Cities. *J Clim* 33:9015–9030. <https://doi.org/10.1175/JCLI-D-19-0961.1>
- Ferré IM, Negrón S, Shultz JM et al (2019) Hurricane Maria’s impact on Punta Santiago, Puerto Rico: community needs and mental health assessment six months postimpact. *Disaster Med Public Health Prep* 13:18–23. <https://doi.org/10.1017/dmp.2018.103>
- Fischer EM, Knutti R (2015) Anthropogenic contribution to global occurrence of heavy-precipitation and high-temperature extremes. *Nat Clim Chang* 5:560–564. <https://doi.org/10.1038/nclimate2617>
- GA García-López (2018) The multiple layers of environmental injustice in contexts of (un) natural disasters the case of Puerto Rico Post-Hurricane Maria 11 101 108 <https://doi.org/10.1089/ENV.2017.0045>.
- Gasparrini A, Guo Y, Hashizume M et al (2015) Mortality risk attributable to high and low ambient temperature: a multicountry observational study. *Lancet* 386:369–375. [https://doi.org/10.1016/S0140-6736\(14\)62114-0](https://doi.org/10.1016/S0140-6736(14)62114-0)
- Green HK, Andrews N, Armstrong B, et al (2016) Mortality during the 2013 heatwave in England - how did it compare to previous heatwaves? A retrospective observational study *Environ Res* <https://doi.org/10.1016/j.envres.2016.02.028>
- Hall TM, Kossin JP (2019) Hurricane stalling along the North American coast and implications for rainfall. *npj Clim Atmos Sci* 2(1):1–9. <https://doi.org/10.1038/s41612-019-0074-8>
- Herring SC, Christidis N, Hoell A et al (2021) Explaining extreme events of 2019 from a climate perspective. *Bull Am Meteorol Soc*. <https://doi.org/10.1175/bams-explainingextremeevents2019.1>
- Holland GJ, Webster PJ (2007) Heightened tropical cyclone activity in the North Atlantic: natural variability or climate trend? *Philos Trans R Soc A Math Phys Eng Sci* 365:2695–2716. <https://doi.org/10.1098/RSTA.2007.2083>
- Hollis D, McCarthy M, Kendon M et al (2019) HadUK-Grid—a new UK dataset of gridded climate observations. *Geosci Data J*. <https://doi.org/10.1002/gdj3.78>
- Huang WTK, Braithwaite I, Charlton-Perez A et al (2022) Non-linear response of temperature-related mortality risk to global warming in England and Wales. *Environ Res Lett* 17:034017. <https://doi.org/10.1088/1748-9326/AC50D5>

- IPCC (2007) Climate Change 2007: the physical science basis Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.
- Keellings D, Hernández Ayala JJ (2019) Extreme rainfall associated with hurricane Maria over Puerto Rico and its connections to climate variability and change. *Geophys Res Lett*. <https://doi.org/10.1029/2019GL082077>
- Kirchmeier-Young MC, Gillett NP, Zwiwers FW et al (2019) Attribution of the influence of human-induced climate change on an extreme fire season. *Earth's Futur*. <https://doi.org/10.1029/2018EF001050>
- Kossin JP (2018) A global slowdown of tropical-cyclone translation speed. *Nature*. <https://doi.org/10.1038/s41586-018-0158-3>
- Kwasinski A, Andrade F, Castro-Sitiriche MJ, O'Neill-Carrillo E (2019) Hurricane Maria effects on Puerto Rico electric power infrastructure. *IEEE Power Energy Technol Syst J* 6:85–94. <https://doi.org/10.1109/JPETS.2019.2900293>
- Lackmann GM (2015) Hurricane Sandy before 1900 and after 2100. *Bull Am Meteorol Soc*. <https://doi.org/10.1175/BAMS-D-14-00123.1>
- Landsea CW (2007) Counting Atlantic tropical cyclones back to 1900 *Eos (Washington DC)* 88 <https://doi.org/10.1029/2007EO180001>.
- Leach NJ, Li S, Sparrow S et al (2020) Anthropogenic influence on the 2018 summer warm spell in Europe: the impact of different spatio-temporal scales. *Bull Am Meteorol Soc*. <https://doi.org/10.1175/BAMS-D-19-0201.1>
- Lloréns H (2018) *Ruin nation* 50 154–159 <https://doi.org/10.1080/10714839.2018.1479468>.
- Lorenz R, Stalhandske Z, Fischer EM (2019) Detection of a climate change signal in extreme heat, heat stress, and cold in Europe from observations. *Geophys Res Lett* 46:8363–8374. <https://doi.org/10.1029/2019GL082062>
- Ma C, Smith T (2020) Vulnerability of renters and low-income households to storm damage: evidence from hurricane Maria in Puerto Rico. *Am J Public Health* 110:196–202. <https://doi.org/10.2105/AJPH.2019.305438>
- Masson-Delmotte, V., P. Zhai, A. Pirani SL, Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy JBR, Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and BZ (2021) IPCC, 2021 Climate Change 2021 the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge Univ Press.
- McCarthy M, Christidis N, Dunstone N et al (2019) Drivers of the UK summer heatwave of 2018. *Weather*. <https://doi.org/10.1002/wea.3628>
- Mitchell D, Heaviside C, Vardoulakis S et al (2016) Attributing human mortality during extreme heat waves to anthropogenic climate change. *Environ Res Lett* 11:074006. <https://doi.org/10.1088/1748-9326/11/7/074006>
- ZA Morris R Anna Hayward Y Otero (2018) The political determinants of disaster risk assessing the unfolding aftermath of hurricane Maria for people with disabilities in Puerto Rico 11 89 94 <https://doi.org/10.1089/ENV.2017.0043>.
- Murakami H, Delworth TL, Cooke WF et al (2020) Detected climatic change in global distribution of tropical cyclones. *Proc Natl Acad Sci U S A*. <https://doi.org/10.1073/pnas.1922500117>
- Niles S, Contreras S (2019) Social vulnerability and the role of Puerto Rico's healthcare workers after hurricane Maria. *Nat Hazards Cent Quick Response Grant Rep Ser* 288:1–9. <https://doi.org/10.13140/RG.2.2.34770.22722>
- Orengo-Aguayo R, Stewart RW, de Arellano MA et al (2019) Disaster exposure and mental health among Puerto Rican youths after hurricane Maria. *JAMA Netw Open* 2:e192619. <https://doi.org/10.1001/jamanetworkopen.2019.2619>
- Otto FEL, Harrington L, Schmitt K et al (2020a) Challenges to understanding extreme weather changes in lower income countries. *Bull Am Meteorol Soc* 101:E1851–E1860
- Otto FEL, Harrington LJ, Frame D et al (2020b) Towards an inventory of the impacts of human-induced climate change. *Bull Am Meteorol Soc*. <https://doi.org/10.1175/bams-d-20-0027.1>
- Otto FEL, Massey N, Van Oldenborgh GJ et al (2012) Reconciling two approaches to attribution of the 2010 Russian heat wave. *Geophys Res Lett*. <https://doi.org/10.1029/2011GL050422>
- Otto FEL, Van Oldenborgh GJ, Eden J, et al (2016) The attribution question *Nat Clim Chang*.
- Pall P, Aina T, Stone DA et al (2011) Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000. *Nature*. <https://doi.org/10.1038/nature09762>
- Parker HR, Boyd E, Cornforth RJ et al (2017) Stakeholder perceptions of event attribution in the loss and damage debate. *Clim Policy*. <https://doi.org/10.1080/14693062.2015.1124750>
- Pasch RJ, Penny AB, Berg R (2017) Tropical Cyclone Report Hurricane Maria.

- Patricola CM, Saravanan R, Chang P (2018) The response of atlantic tropical cyclones to suppression of African Easterly waves. *Geophys Res Lett* 45:471–479. <https://doi.org/10.1002/2017GL076081>
- Patricola CM, Wehner MF (2018) Anthropogenic influences on major tropical cyclone events. *Nature* 563:339–346. <https://doi.org/10.1038/s41586-018-0673-2>
- Perkins-Kirkpatrick SE, Stone DA, Mitchell DM et al (2022) On the attribution of the impacts of extreme weather events to anthropogenic climate change. *Environ Res Lett* 17:024009. <https://doi.org/10.1088/1748-9326/AC44C8>
- Philip S, Kew S, van Oldenborgh GJ et al (2020) A protocol for probabilistic extreme event attribution analyses. *Adv Stat Climatol Meteorol Oceanogr* 6:177–203. <https://doi.org/10.5194/ASCMO-6-177-2020>
- Philip S, Sparrow S, Kew SF et al (2019) Attributing the 2017 Bangladesh floods from meteorological and hydrological perspectives. *Hydrol Earth Syst Sci*. <https://doi.org/10.5194/hess-23-1409-2019>
- Prior J, Beswick M (2007) The record-breaking heat and sunshine of July 2006. *Weather*. <https://doi.org/10.1002/wea.101>
- Reed KA, Stansfield AM, Wehner MF, Zarzycki CM (2020) Forecasted attribution of the human influence on Hurricane Florence. *Sci Adv*. <https://doi.org/10.1126/sciadv.aaw9253>
- Reed KA, Wehner MF, Stansfield AM, Zarzycki CM (2021) Anthropogenic influence on hurricane Dorian's extreme rainfall. *Bull Am Meteorol Soc* 102:S9–S15. <https://doi.org/10.1175/BAMS-D-20-0160.1>
- Risser MD, Wehner MF (2017) Attributable human-induced changes in the likelihood and magnitude of the observed extreme precipitation during hurricane Harvey *Geophys Res Lett* 44 12 457 12 464 <https://doi.org/10.1002/2017GL075888>.
- Russell JO, Aiyyer A, White JD, Hannah W (2017) Revisiting the connection between African Easterly Waves and Atlantic tropical cyclogenesis. *Geophys Res Lett* 44:587–595. <https://doi.org/10.1002/2016GL071236>
- Scaramutti C, Salas-Wright CP, Vos SR, Schwartz SJ (2019) The mental health impact of hurricane Maria on Puerto Ricans in Puerto Rico and Florida. *Disaster Med Public Health Prep* 13:24–27. <https://doi.org/10.1017/dmp.2018.151>
- Schaller N, Kay AL, Lamb R et al (2016) Human influence on climate in the 2014 southern England winter floods and their impacts. *Nat Clim Chang*. <https://doi.org/10.1038/nclimate2927>
- Seneviratne SI, Zhang X, Adnan M, et al (2021) 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* 1513–1766.
- Seong M-G, Min S-K, Kim Y-H et al (2021) Anthropogenic greenhouse gas and aerosol contributions to extreme temperature changes during 1951–2015. *J Clim* 34:857–870. <https://doi.org/10.1175/JCLI-D-19-1023.1>
- Shepherd TG (2021) Bringing physical reasoning into statistical practice in climate-change science. *Clim Change* 169:1–19. <https://doi.org/10.1007/S10584-021-03226-6/FIGURES/2>
- Shepherd TG (2016) A common framework for approaches to extreme event attribution *Curr Clim Chang Reports*.
- Sobel AH, Camargo SJ, Hall TM, et al (2016) Human influence on tropical cyclone intensity *Science* (80-.) 353:242–246.
- Sparrow S, Huntingford C, Massey N, Allen MR (2013) The use of a very large atmospheric model ensemble to assess potential anthropogenic influence on the UK summer 2012 high rainfall totals. *Bull Am Meteorol Soc* 94:S36–S38
- Stott PA, Christidis N, Otto FEL et al (2016) Attribution of extreme weather and climate-related events. *Wiley Interdiscip Rev Clim Chang*. <https://doi.org/10.1002/wcc.380>
- Stott PA, Stone DA, Allen MR (2004) Human contribution to the European heatwave of 2003. *Nature* 432:610–614. <https://doi.org/10.1038/nature03089>
- Strauss B, Orton P, Bittermann K et al (2021) Economic damages from Hurricane Sandy attributable to sea level rise caused by anthropogenic climate change. *Nat Commun* 12:15. <https://doi.org/10.1038/s41467-021-22838-1>
- Sweet W, Zervas C, Gill S, Park J (2013) Hurricane sandy inundation probabilities today and tomorrow. *Bull Am Meteorol Soc* 94:S17–S20
- Trenberth KE, Cheng L, Jacobs P et al (2018) Hurricane Harvey links to ocean heat content and climate change adaptation. *Earth's Futur*. <https://doi.org/10.1029/2018EF000825>
- van Oldenborgh GJ, van der Wiel K, Kew S et al (2021) Pathways and pitfalls in extreme event attribution. *Clim Change* 166:1–27. <https://doi.org/10.1007/S10584-021-03071-7/FIGURES/5>
- Van Oldenborgh GJ, Van Der Wiel K, Sebastian A et al (2017) Attribution of extreme rainfall from Hurricane Harvey, August 2017. *Environ Res Lett*. <https://doi.org/10.1088/1748-9326/aa9ef2>

- Vicedo-Cabrera AM, Sera F, Tobias A et al (2019) Heat-related mortality impacts attributed to climate change. *Environ Epidemiol* 3:414. <https://doi.org/10.1097/01.ee9.0000610636.25240.e8>
- Vosper EL, Mitchell DM, Emanuel K (2020) Extreme hurricane rainfall affecting the Caribbean mitigated by the Paris agreement goals *Environ Res Lett* 15:104053. <https://doi.org/10.1088/1748-9326/AB9794>
- Walsh-Russo C (2018) Planning for the unimaginable: Puerto Rico and strategies for climate-change adaptation <https://metropolitix.org/Planning-for-the-Unimaginable-Puerto-Rico-and-Strategies-for-Climate-Change.html> Accessed 3 Sep 2020.
- Walsh KJE, McBride JL, Klotzbach PJ et al (2016) Tropical cyclones and climate change. *Wiley Interdiscip Rev Clim Chang*. <https://doi.org/10.1002/wcc.371>
- Wang SYS, Zhao L, Yoon JH et al (2018) Quantitative attribution of climate effects on hurricane Harvey's extreme rainfall in Texas. *Environ Res Lett* 13:054014. <https://doi.org/10.1088/1748-9326/AABB85>
- Wang SYS, Zhao L, Yoon JH et al (2018b) Quantitative attribution of climate effects on hurricane Harvey's extreme rainfall in Texas. *Environ Res Lett*. <https://doi.org/10.1088/1748-9326/aabb85>
- Weinkle J, Landsea C, Collins D et al (2018) Normalized hurricane damage in the continental United States 1900–2017. *Nat Sustain* 1:808–813. <https://doi.org/10.1038/s41893-018-0165-2>
- Weiss L, Lebrón M, Chase M et al (2018) Eye of the storm: colonialism, capitalism, and climate in the Caribbean. *NACLA Rep Am* 50:109–111. <https://doi.org/10.1080/10714839.2018.1479417>
- Williams L, Erens B, Ettelt S, et al (2019) Evaluation of the heatwave plan for England final report.
- Woo G (2019) Downward counterfactual search for extreme events. *Front Earth Sci*. <https://doi.org/10.3389/feart.2019.00340>
- WWA (2022) Without human-caused climate change temperatures of 40°C in the UK would have been extremely unlikely – World Weather Attribution. <https://www.worldweatherattribution.org/without-human-caused-climate-change-temperatures-of-40c-in-the-uk-would-have-been-extremely-unlikely/>. Accessed 15 Sep 2022.
- Zakrisson TL, Valdés DM, Shultz JM (2020) The medical, public health, and emergency response to the impact of 2017 hurricane Irma in Cuba. *Disaster Med Public Health Prep* 14:10–17. <https://doi.org/10.1017/DMP.2019.71>
- Zscheischler J, Lehner F (2022) Attributing compound events to anthropogenic climate change. *Bull Am Meteorol Soc* 103:E936–E953. <https://doi.org/10.1175/BAMS-D-21-0116.1>

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