ANNUAL REVIEWS

Annual Review of Environment and Resources

Attribution of Extreme Events to Climate Change

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Annu. Rev. Environ. Resour. 2023. 48:813–28

First published as a Review in Advance on August 22, 2023

The *Annual Review of Environment and Resources* is online at environ.annualreviews.org

https://doi.org/10.1146/annurev-environ-112621-083538

Keywords

extreme events, attribution, climate change, climate vulnerability

Abstract

Within the past decade, the attribution of extreme weather events and their impacts has enabled scientists, the public, and policymakers alike to connect real-world experiences of extreme weather events with scientific understanding of anthropogenic climate change. Attribution studies of recent extreme weather events have formed a new and important line of evidence in the most recent Intergovernmental Panel on Climate Change (IPCC) assessment report understanding present-day impacts of climate change. IPCC studies using different methods of event attribution have been assessed together, highlighting that these differences are smaller than the academic discourse on the methods suggests. This development raised two important research questions the science needs to answer: First, how do we formally combine attribution statements using highly conditional methods with probabilistic assessments of how climate change alters the likelihood and intensity of extreme weather events? Second, under what circumstances are individual attribution studies still necessary and to what extent do existing attribution studies provide enough information to answer societal questions? Furthermore, the scientific development still leaves important gaps, particularly in countries of the Global South, leading to ethical questions around the need and requirement of attribution of extreme events in policy contexts, informing adaptation and loss and damage and the role of vulnerability.

Contents

1. INTRODUCTION

Since the last review of the attribution of extreme weather events to anthropogenic climate change (1) published in this journal, the science has emerged from an arguably controversial new field of research to an established line of evidence in understanding the impacts of anthropogenic climate change. The publication of the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) in August 2021 that for the first time reviewed the literature base of event attribution studies marks an important caesura (2). Attribution, and particularly attribution of extreme events, forms an important additional new line of evidence (3) and is the basis of some of the key facts, stated in the *Summary for Policymakers*. Statement A3—"Human-induced climate change is already affecting many weather and climate extremes in every region across the globe. Evidence of observed changes in extremes such as heat waves, heavy precipitation, droughts, and tropical cyclones, and, in particular, their attribution to human influence, has strengthened since AR5" (4, p. 8)—is one example. Particularly noticeable is that this is stated without any uncertainty and confidence language, which means it is a fact, on the same level of scientific confidence as the statement that human influence has warmed the climate. This and the rest of the assessment on the changing nature of extreme events is not informed by one specific method of extreme event attribution but, rather, studies using a range of methods and data. This reflects a key development since the 2017 review, that the literature on extreme event attribution has largely moved on from debating what the correct method to undertake a study is to a broad acceptance that the differences are gradual (5) rather than fundamental in many cases and that different methods serve different purposes. That there are now more than 500 individual attribution studies (see here: **https://www.carbonbrief.org/mapped-how-climate-change-affects-extreme-weather-around-the-world/**) also means that general statements about how different types of extreme events are changing in different regions of the world due to anthropogenic climate change can now be made based on the existing literature, without necessarily undertaking a bespoke attribution study. However, there are major geographical differences, with large knowledge gaps in the Global South (6).

The second major development in the attribution of extreme events is on the attribution of the impacts of these events on, e.g., human health (7, 8), economic costs (9–11), or ecosystem impacts (12) and how factors other than climate change can meaningfully be assessed within the framework of extreme event attribution (13). These two areas are currently the frontier of research and are discussed below. On the one hand, there is the question of when and under what circumstances attribution studies are needed, useful, and necessary and what general conclusions about the changing nature of extreme events can be drawn; on the other hand, there is an increasing body of literature focusing on how to go from weather to actual impacts and how to disentangle drivers of disasters, rather than just drivers of the hazard. This is particularly relevant with respect to the

Event attribution: estimating the relative contribution of multiple causal factors, e.g., anthropogenic climate change, to an extreme weather event

LOSS AND DAMAGE

Loss and damage has been part of the United Nations Framework Convention on Climate Change (UNFCCC) negotiations from the start in the early 1990s, pushed for decades in international climate negotiations particularly by the so-called least-developed countries, often against negotiators from the Global North. These countries have experienced first-hand the extremely costly losses and damages from extreme weather events, as well as the associated developmental setbacks, such as increasing poverty, inequity, and inequality in human health (14). In 2013, loss and damage formally entered the UNFCCC with the establishment of the Warsaw International Mechanism for Loss and Damage associated with Climate Change Impacts (Warsaw Mechanism) at the nineteenth Conference of the Parties (COP) (November 2013) in Warsaw, Poland, to address loss and damage associated with impacts of climate change, in particular in vulnerable countries. Two years later, the Paris Climate Agreement was established, addressing for the first time loss and damage as clearly distinct from mitigation and adaptation. International climate policy now rests on three pillars: loss and damage (Article 8), adaptation (Article 7), and mitigation (Articles 4, 5, 6). In Article 8 of the Paris Agreement, parties agreed to enhance understanding, action, and support with respect to loss and damage occurring due to the adverse effects of climate change. Still today, there is no definition of what constitutes loss and damage, and interpretations between constituents of the Paris Agreement divert considerably (15). Consequently, there are no metrics to identify loss and damage from either slow-onset or extreme weather events.

In December 2022, at the COP27, following a series of devastating extreme weather events in 2022—including heat in India and Pakistan (16), flooding in Pakistan (17) and West Africa, droughts across the northern hemisphere (18), and tropical cyclones in, e.g., Southeastern Africa, the United States, and the Caribbean (19)—loss and damage got further strengthened in the UNFCCC with the establishment of a Loss and Damage fund. The Executive Committee of the Warsaw Mechanism is responsible for developing rules and procedures for setting up the fund, and providing guidance on its use. This development puts urgency on addressing the current lack of evidence to identify what constitutes loss and damage and evidence thereof. Given that climate change without further qualification denotes anthropogenic climate change, event attribution can play a potentially important role. What precisely this role might be, however, is at present unclear and a pressing research question.

growing importance of addressing loss and damage within global climate policy and damages more generally in insurance, the courts, and national politics (see the sidebar titled Loss and Damage).

Although the 2017 review paper was comparably technical and introduced different methodologies, this update is providing more questions than answers and shows the current state of the debate. The methods introduced in 2017 have not changed with respect to their underlying ideas, and we refer the reader to this paper (1) for a primer. What has changed, however, is the scale at which they have been implemented and the public and political recognition of this not-so-new branch of science. Thus, ethical rather than scientific and practical questions dominate the current discourse and are thus reviewed here.

Other review papers highlight the current state of knowledge on specific types of extremes (20), some of the prevailing myths about the science (21), and how the socializing of the science has influenced climate litigation and mobilized communities (22). The chapter on extremes in the latest IPCC assessment report provides a very concise overview of the state of attribution science (2).

2. METHODS FOR EVENT ATTRIBUTION

All methods of event attribution typically involve the comparison of observed historical changes, simulated under observed forcings, to a counterfactual climate simulated in the absence of all or some components of anthropogenic forcing. This can be done either in a quantitative, statistical way, in which case the results are probabilistic, or by simulating the evolution of an event under a different forcing to gather a process-based attribution statement (2, 3, 23, 24). The former is usually called probabilistic event attribution, whereas approaches that focus on the evolution of an event under a specific forcing are often called storyline approaches. Conceptually, the storyline approach focuses on the physical dynamics of or state of the atmospheric circulation that led to the event in question. Studies thus focus on how these dynamics could have unfolded differently given the impact of climate change on the thermodynamics of the climate system. Examples of these approaches might find, e.g., that 50% of the magnitude of a given event under the same dynamical conditions as observed can be explained by natural variability (25). The approach does not provide assessments of the overall likelihood of an event, which in contrast is the starting point for typical probabilistic approaches that then go on to assess whether and to what extent this likelihood and the intensity of the event have changed due to anthropogenic climate change. For example, Ciavarella et al. (26) found that the prolonged heat in Siberia in 2020 was made at least 600 times more likely by human-induced climate change and that an event of the same likelihood as the heat had today (estimated to be approximately a 1-/130-year event) would have been two degrees cooler in a world without climate change. However, as described by Jézéquel et al. (5), there are many studies incorporating elements of both methods, by, for example, defining analogue dynamical situations and assessing how the relative frequency of such situations has changed; in the case of the Mediterranean storm Apollo of 2021, for example, the frequency of analogue situations leading to heavy storms increased significantly in the month of September when the storm occurred (27). Thus, a clear distinction between different methods is only possible in pathological cases and methods are often differing in the degree of conditioning rather than fundamentally. All methods follow a process of similar steps in their assessment, which further underpins the similarities, additionally corroborated by the IPCC decision to assess all attribution studies together (2) rather than separating by methodology.

The 2017 review describes six steps a research team needs to undertake in order to conduct an attribution study of an extreme weather event. While these have not fundamentally changed, more recent work (3, 28) has identified additional steps, representing either decisions or activities that are typically undertaken. These steps are largely independent of the concrete method and represent important decisions that are explicitly or implicitly undertaken. **Figure 1** summarizes these steps and highlights key requirements to undertake them with scientific integrity.

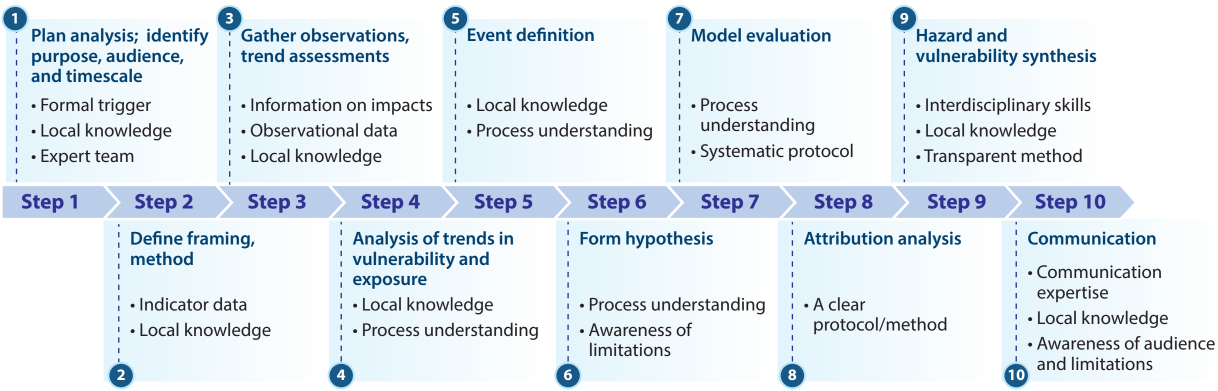

Figure 1

A schematic representation of the steps in the process of an event attribution study, including the key requirements for each step. The steps are independent of methods and have been adapted with permission from earlier reviews to include the important assessment of vulnerability and exposure [1 (CC BY 4.0), 28].

Step 1 is the decision to actually undertake an attribution study for a specific event. Given the large imbalance between studies in the Global North compared to the Global South (see below), this step requires ethical considerations but will also include decisions on who the audience of a study is, which has implications on the timescales; e.g., a paper for an academic audience is usually not urgent, whereas if the general public or policymakers are the main audience, a rapid study might be more appropriate. In any case, local knowledge about the meteorology but also climate vulnerability is required in order to assess whether a study is feasible. Step 2 follows once the decision has been made that a study is to be undertaken. This step basically describes a decision on methodology, depending on intended audience, complexity of the event (e.g., if climate models are not expected to be good enough, a storyline approach would be chosen over a statistical one), and available data and expertise. Step 3 consists of an initial assessment of observed data and requires the availability of such data, expertise in judging their quality, and, in particular, an assessment of damages and vulnerability to link meteorological data with observed impacts; the assessment could be aborted if no sufficient data are available. Step 4 consists of an initial analysis of data sets and testing of the differences in these trends depending on indicators of the event and geographical and temporal scales. Step 5 consists of the formal definition of the event, determining variables and geographical and temporal scales. Step 6 is often undertaken implicitly also by the researchers themselves and consists of formulating a hypothesis to test in the subsequent attribution step. In a storyline approach, this is, e.g., assessing the role of the thermodynamic changes in the climate system (see Section 3, below), whereas in most probabilistic approaches the null hypothesis would be that climate change did not alter the likelihood of an event occurring. Step 7 is testing whether available climate models are fit for the purpose identified in the previous steps. Ideally this is done in a systematic way so that different attribution study results are better comparable with each other (28–31). Again, this is a step in the process that could lead to a study being aborted if no suitable models are found. Step 8 consists of the actual attribution analysis in models and observations and typically results in either a probability ratio describing the change in likelihood due to human-induced climate change or the fraction of attributable risk (FAR), which is calculated by subtracting the probability ratio from 1. In addition or alternatively an intensity change is provided, given in percentages (e.g., for rainfall events) or the unit the defined event indicator is measured in (e.g., degrees centigrade for heat extremes). For storyline methods, usually the latter is given but conditional under the assumption that the event occurred. Step 9 consists of taking the results from Step 8 and the vulnerability and exposure assessments together to formulate an overarching conclusion. For example, "Factors other than climate change are the main drivers of recent food insecurity in Southern Madagascar" (32; see also 33). Again this step requires local expertise and interdisciplinary skills in order to reflect limitations and strength of the analysis appropriately. Step 10, the final step, can in some cases be straightforward if the audience is academic and the study a peer-reviewed paper; in other cases, it requires communication expertise to translate scientific findings into messages that can be understood by media and general public alike in a way that reflects the caveats appropriately.

Climate vulnerability: the predisposition to being adversely affected by weather and climate-related events and long-term changes and variability in climate; encompasses various concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt

These steps are not always considered with the same level of detail and rigor, but they capture the essence of what researchers are doing when undertaking an attribution study. In the face of this growing body of literature, a scientific discourse unfolded that particularly concerns the very first step, and is discussed in the following section.

3. DO WE (STILL) NEED ATTRIBUTION?

To answer this question, there is still another question a small but important part of the literature is grappling with: whether attribution of extreme weather events was ever needed, is useful, or in fact does more harm than good. Although those arguments come from an ethical perspective and are posed largely by authors not doing active research on climate science, they should not be easily dismissed. Olsson et al. (34) identify two key problems with the most commonly used approach of extreme event attribution, the probabilistic approach introduced in Reference 1 and considerably developed since in Reference 28. This approach, as Olsson et al. point out, indeed depends on the availability of data, and if only the statistical approach that is the core of the method is used to calculate an overarching result, the latter is prone to being too conservative (35). This means, in particular in data-poor regions where the uncertainty around the assessment of changing likelihoods is large, results are likely too conservative and if taken in a global context data-rich regions might look more affected by climate change than their data-poor counterparts. A purely statistically driven interpretation of probabilistic methods thus introduces type II errors, i.e., false negatives, while trying to avoid type I (false positives) errors (36, 37). Lusk (38) and Olsson et al. (34) conclude from this assessment that the probabilistic approach is unethical and, thus, a storyline approach would be favorable.

Although the analysis is certainly correct, and in line with earlier studies highlighting the tendency to being too conservative (36, 39–41), the conclusion shows an unfortunate mischaracterization of the framework of probabilistic event attribution or, rather, the flexibility of that framework. Although no gold-standard methodology to probabilistic attributing of extreme events exists, a few best-practice approaches have emerged (3, 28, 42) that employ quantitative assessments and statistical tools to synthesize hazards, but also allow for and require expert judgement and the inclusion of other lines of evidence to inform overarching results. On the one hand, differentiated weighting of data sources is possible, as well as the inclusion of, in particular, drivers other than climate change. It has been suggested that such approaches should in fact use a Bayesian framework (36), which would allow the assumption that climate change in fact does play a role to be incorporated formally in the assessment, whereas standard statistical approaches do not assume prior knowledge. To my knowledge, such a framework has not been employed in a concrete attribution study. However, there has been consequent inclusion of future projections when developing attribution statements (43) that allow for signals that have not yet emerged to be identified. Many recent studies have employed these (26, 42, 44, 45). In addition, in some recent studies, similarly to how IPCC assessments are derived, several lines of evidence are employed and the conclusion, even quantitative, is based on this combination. For example, a recent study on soil moisture drought in Western Europe (18) using the probabilistic framework found that, combining all lines of evidence, human-induced climate change made the 2022 root zone soil moisture drought approximately three to four times more likely and the surface soil moisture drought approximately five to six times more likely. Had a statistical synthesis been used, the result would have been "not significant," but by taking the process understanding, the observed changes, and future projections into account, more weight was given to the best estimate, and thus potentially a type I error was avoided. Although the storyline approach avoids these types of errors more easily, by relying less on climate models' ability to simulate correct statistics, the approach, by assessing only the thermodynamic changes (46), also does not allow assessment of the full impact of climate change on an extreme weather event. Storyline attribution statements must therefore be considered, as Reed et al. (19, p. 1) point out "as incomplete assessments of the effect of anthropogenic climate change on extreme weather events and conditional on the event's underlying existence."

Thus, undertaking extreme event attribution as a purely data-driven, statistical exercise would indeed be ethically questionable. However, this is not a problem of event attribution, or probabilistic event attribution per se, but the concrete implementation of the method. Above are examples of how an overly conservative interpretation can be avoided. Such methodological developments are, however, relevant to not only avoiding misinformation but also making attribution studies most useful. In addition to simply identifying present-day impacts of anthropogenic climate change, attribution studies should also inform adaptation and be relied upon to inform compensation claims. With respect to the former, the inclusion of future projections is particularly relevant. Although important with respect to the attribution of all types of extreme events, the inclusion of future projections is particularly important for heat wave attribution, where in a rapidly changing climate present-day estimates of occurrence frequency will be outdated almost immediately (47).

The circumstances under which attribution studies can be relied upon have been discussed in particular in the context of the courts. Climate litigation has become an increasingly important lever toward achieving more ambitious climate goals, but success has so far been limited to cases aiming to achieve mitigation goals (48). Recent publications argue that developments in extreme event attribution could change this and lead to favorable outcomes for compensation-based claims on concrete losses and damages (49–51). Most currently filed cases do not make use of the science, even when it would support the claims (52). While the lack of sufficient evidence has likely not been the reason for the unsuccessfulness of these cases up to today as cases have failed early in the process on judicial grounds (53), the evidence will need to be better as courts increasingly accept that climate litigation claims are legitimate struggles for justice and thus accept cases and scrutinize the evidence (22). This anticipation of new court cases requiring scientific evidence for losses and damages has sparked research on the link between legal and scientific causality within extreme weather events. Some scholars came to the conclusion that the existence of different methodologies that lead to quantitatively very different attribution statements could lead to a battle of the experts (54). Avoiding such situations requires the existence of a so-called causal field (55): a field of literature of accepted methodologies and other studies, applying these methodologies in different regions and on different types of extremes, against which an individual study can be assessed. The IPCC assessment of this literature referred to above (2) demonstrates that at least for some types of extreme events such a causal field exists, independent of methodological differences. Although far from complete, the past few years of research in the science of extreme event attribution have brought us closer to an inventory of the impacts of climate change, at least on extreme weather (31, 56). Once again, large gaps still exist, particularly with respect to extremes impacting the Global South, where event attribution is facing the same challenges as climate science in general (6, 57–59). This has ethical consequences in the use of attribution information, in particular with respect to loss and damage (see below).

That there is now a solid body of literature on event attribution means that, on the one hand, solid scientific information on impacts of climate change is more readily available for media reporting, climate litigation, and NGO campaigning without dedicated or rapid attribution assessments. On the other hand, this begs the question of whether and under what circumstances individual attribution statements are still necessary. The answer lies in the required detail and quantification. To confirm that heat waves have become more likely and more intense, no new study is necessary; similarly, there is ample information to show that short, heavy rainfall (on the order of 1–5 days) has become more intense (see section 11.4.4 of Reference 2, and references therein). For other types of extremes, like droughts, wildfires, and tropical cyclones, synthesized information for attribution studies is only regionally applicable (20). This does mean that in many parts of the world, our understanding of how these extremes change under global warming is still limited; however, even when the sign of the change is known a priori, the magnitude can be very different locally. Furthermore, the processes behind changing extreme events are still not well understood. This is also true for allegedly easy attribution studies like those on heat waves. In most parts of the world, the observed trends in extreme heat are very different (e.g., considerably larger in Europe or Australia and smaller in the United States or India) (60) without any obvious reasons for these discrepancies. Another example are some recent attribution studies on tropical cyclones that report an increase in heavy precipitation scaling at double the expected Clausius-Clapeyron relationship of 6–7% per degree of warming (11, 61–63), suggesting a change in the atmospheric dynamics as well as an increase due to warming alone. Disentangling thermodynamic changes from dynamic ones is important to understand ultimately the drivers of change. This is necessary to be better able to judge climate models' fitness for purpose and understand, e.g., which storylines need to be developed to explore worst-case scenarios and ultimately which available attribution studies are reliable to tell us something about the real world. Again, progress on this question would be best achieved by combining lines of evidence and methodological approaches to fully understand the role of climate change in individual extreme events. A combination of storyline and probabilistic approaches, in particular those making use of existing literature on similar events, has been employed to understand the role of climate change in heavy summer rainfall in Japan (64); the study found that climate change increased the July 2020 heavy rainfall in Japan's Kyushu District by approximately 15% and also increased the likelihood of such a rainfall system. This is one of currently still few albeit increasing examples of how moving beyond theoretical debates about the best approach to employing the knowledge we have to practical applications moves event attribution from a branch of climate science toward a tool that can ultimately help disentangle different drivers of disasters. Ultimately, this could provide scientific evidence in support of some of the most pressing political agendas on adaptation, resilience, and loss and damage.

4. TOWARD UNDERSTANDING AND DISENTANGLING DRIVERS OF DISASTERS

Some of the early and consistent criticisms of extreme event attribution, similar to physical climate science more generally, is the focus on the hazard; i.e., the extreme weather event leads to an ignorance of the huge role vulnerability and exposure are playing in turning extreme weather into disasters (65, 66). As argued in References 65 and 66 and references therein, current practices, in particular but not limited to communicating extreme event attribution results, highlight the role of anthropogenic climate change to a degree that hinders rather than helps disentangling and addressing all drivers of disasters, including those on local scales. Research on this topic is limited but has found that even if the underlying scientific study does include an assessment of the role of vulnerability, the communication focuses on the hazard component alone, and thus the only message that is received is that of the importance of climate change (67–69). This framing continues to perpetuate the notion that disasters are natural or acts of a deity and takes agency away from local authorities but also individuals to decrease vulnerability (70). Including vulnerability assessments as an integral part of any attribution study has been recognized by the climate attribution research community as rendering extreme weather event attribution studies usable (13, 28). There is no inherent reason why this should not be possible, despite it often being referred to as an inherently problematic aspect of event attribution. In fact, precisely because event attribution aims to answer the question of the role of climate change in events that have actually occurred in the real world, they perpetuate neither a climate- nor vulnerability-centric view but integrate them to provide a more holistic assessment of drivers of disasters (71). This is a challenge, as truly interdisciplinary science is still rare and not many methods or approaches have been socialized, but it is a challenge scientists are taking on. Recent studies (17, 32, 33) highlight the importance vulnerability is playing in addition to the hazard. **Figure 2** illustrates the various ways different aspects of vulnerability drive the impacts of extreme weather events. Looking at these complex interactions, the challenge of including these drivers systematically in attribution studies becomes apparent as does, equally, its importance. It is easy to see that vulnerability is sometimes the main

Figure 2

A visual adapted from Otto et al. (17) representing factors contributing to vulnerability of households (HHs) to floods in Pakistan. The figure is categorized by types of vulnerability developed in Reference 76 based on empirical evidence and evidence from studies across Pakistan. The figure illustrates the complex and interacting ways vulnerability affects the impacts of extreme weather events. Figure adapted with permission from Reference 17.

driver of any impact, in particular when hazards are not actually extreme (72–74) or when climate change is not playing a role at all (75).

When the aim of the attribution study is to really understand the drivers of an extreme event and the impacts, the definition of the event becomes crucially important and determines the result of the assessment. Leach et al. (77) have shown how different ways of defining a heat wave lead to very different attribution statements, a fact also highlighted in the 2017 review. There is generally no right or wrong answer, but an event definition can be more or less relevant and focusing the event definition of some aspects of a more complex event only can lead again to a too conservative estimate of the role of climate change. For example, if a drought is assessed only based on rainfall, a crucial rule of temperature might be overlooked if in fact it was a hot and dry event (78, 79) instead. There will always be a trade-off between defining and analyzing an extreme weather event that can be easily characterized by weather and climate variables, e.g., temperature and rainfall, and the actual drivers of the impacts, which are often compound events (80). Increasingly, event attribution is, however, moving toward more impact-related metrics, e.g., fire weather indices (45, 81, 82) or floods rather than merely rainfall (83–85). As hydrological models are conceptionally very different from each other, in contrast to climate models which ultimately are all based on the Navier-Stokes equation, an ensemble approach to attributing impacts is often not possible. Here, expert judgements on the most appropriate tools have higher relevance than in the attribution of weather events alone (see section 11.5.4 of Reference 2).

In cases where impacts are directly related to the weather events, e.g., health impacts from extreme temperatures or economic costs of water damages from heavy rainfall, no additional impact modelling is necessary. For some of these events studies have been published attributing these impacts to anthropogenic climate change. One method that has been developed to do this type of assessment is to use the FAR (see Section 2) and multiply this by the damage function describing the incurred losses (9, 10, 86, 87); this is a similar approach that has also been used to attribute health impacts (7). Although this is a simple method that is easy to apply and understand, it relies on the assumption that impacts like the one observed and all impacts from similar or worse events are leading to similar or worse impacts. This assumption is easy to justify when the event has reached a threshold that makes the difference between damages and no damages, e.g., a dam breaking, but is less appropriate with respect to more continuous impacts. Recent work (88) has suggested instead to use delta intensity changes instead of FAR-based approaches to conduct damage attribution. More research is needed on how and when certain assumptions hold, and it is urgent given that employing the FAR-based approach estimated that \$67 billion of the \$90 billion in damages from Hurricane Harvey are attributable to climate change (10) while the delta intensity-based method estimated the attributable economic damages to be \$13 billion (11). This discrepancy is considerable and needs to be better understood to improve our understanding of the impacts of anthropogenic climate change and thus ultimately allow for an assessment of loss and damage (89).

Loss and damage in the UNFCCC negotiations has been discussed for many years and been implemented as a third pillar of international climate policy next to adaptation and mitigation in the Paris Agreement (90). Although the intention behind including loss and damage in the UNFCCC has been to aid vulnerable countries least responsible for historic greenhouse gas emissions to deal with already occurring damages and losses from anthropogenic climate change, there is no formal definition of what loss and damage actually means and different groups of negotiators have very different views (15). Furthermore, within the IPCC, climate impact assessment has historically been undertaken independent of attribution and thus evidence of actual losses and damages from human-induced climate change could not be disentangled from natural variability. This has changed with the most recent IPCC assessment report, which does include an attribution statement in the impacts' overviews provided (91). These assessments do not directly underpin the UNFCCC negotiations, in particular given the large gaps in assessments in the Global South as compared to the Global North (4, 6, 66), but will inform what typical losses and damages are, not only within the UNFCCC but also in national and regional governance and litigation (52). This is already the case, whether we like it or not, so improving research methods for data-poor regions and understanding what events we are actually most vulnerable to and how such events compounding in time and space can be attributed will be necessary to close remaining gaps that currently preclude efforts to more systematically conduct attribution studies (31, 56). Attribution has changed public and political understanding about what climate change means today, how much it costs, and who is paying the price. By closing the research gaps mentioned above, it can also be a tool to help support solutions. This is not only a research effort but also a communication challenge (48).

5. CONCLUSION

The usage of attribution studies in the media, but also within courts, NGOs, and other realms of decision making, shows a clear need in society for scientific evidence on the changing intensities and frequencies of extreme events. This means that in the face of certainly existing ethical and methodological challenges not doing attribution or focusing on simple cases only is not an option. Instead of competing for the hegemony of ideas between communities, we need to urgently learn how to efficiently combine different methodologies that will allow for rapid attribution studies still to be provided, but not at the expense of underestimating the role of climate change in data-poor regions. Similarly, research and communication efforts need to be strengthened to ensure the role of vulnerability and exposure is adequately incorporated in all attribution studies, whether they are intended to be rapidly disseminated or published in the peer-reviewed literature only. By focusing on real-world events, attribution science cannot be performed as *l'art pour l'art*, as all results of every study have consequences for the real world, and type II errors, especially if occurring systematically in the Global South, can have fatal consequences. This is a challenge for most natural scientists trained to avoid type I errors at all costs; in this rapidly warming world we live in, however, it is a challenge we need to take on.

SUMMARY POINTS

1. The science of event attribution has matured to provide an independent and important line of evidence linking climate observations and projections to inform climate policy.
2. Different methods of attributing extreme weather events are not as distinct as some scholars suggest and would ideally be combined to provide a complete understanding of how human-induced climate change affects impactful weather- and climate-related events.
3. There currently exists a large imbalance between understanding of extreme weather and climate change in the Global North compared to the Global South.
4. New political developments, in particular the UNFCCC Loss and Damage fund, require harmonization of currently existing approaches to extreme event attribution.

FUTURE ISSUES

1. Communication of extreme event attribution is often limited to specialized audiences or misunderstood; more research and testing of attribution statements are needed for studies to be able to inform real-world decisions.
2. Research capacity will need to increase dramatically in the Global South to close the gap between the Global North and Global South with regard to available evidence for the impacts of climate change.
3. Researchers must develop and socialize a framework for event attribution that combines advances from both storyline and probabilistic approaches.
4. Event attribution research must include systematically vulnerability and exposure assessments.

DISCLOSURE STATEMENT

Acknowledging that no review can be completely objective—e.g., authors are often active researchers in the fields about which they write—and that her leadership role for the World Weather Attribution Initiative could be seen as bias by some, the author is not aware of any other affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

The author was supported by the H2020-funded project XAIDA under grant 101003469.

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