



Integrating attribution with adaptation for unprecedented future heatwaves

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Abstract

Citizens in many countries are now experiencing record-smashing heatwaves that were intensified due to anthropogenic climate change. Whether today's most impactful heatwaves could have occurred in a pre-industrial climate, traditionally a central focus of attribution research, is fast becoming an obsolete question. The next frontier for attribution science is to inform adaptation decision-making in the face of unprecedented future heat.

Keywords Climate change · Heatwave · Attribution · Adaptation

Prior to the 2000s, communication to the wider public about the importance of rising greenhouse gas emissions and a warming planet was challenging. Limited evidence existed of the impacts of climate change on human and natural systems, while projections of significant changes later in the century usually relied either on global mean or large-scale properties — hard to place meaningfully in local contexts and insufficient to address runaway emissions growth. When an extreme flood or heatwave made news headlines, the climate research community presented these phenomena as unique weather events, too rare and complex to be linked directly to ongoing anthropogenic warming (Stott et al. 2016).

This changed when a 2004 analysis (Stott et al. 2004) demonstrated an extreme heatwave over continental Europe — fresh in the minds of the people who suffered through the impacts that previous summer, including the deaths of 70,000 family members and friends (Robine et al. 2008) — was more severe and at least twice as likely to have occurred because of climate change. By contextualising a changing climate as affecting extreme weather events and impacts that we suffer today, the development of a new field of climate science, extreme event attribution, emerged (Otto 2017).

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Subsequent advances in the science of event attribution have been transformative in communicating to the wider public that anthropogenic climate change is in fact a present-day phenomenon (Reser et al. 2014; Osaka and Bellamy 2020). Event attribution studies typically focus on the frequency and magnitude of meteorological variables in climates with higher and lower levels of anthropogenic forcing. Studies can focus on the change in frequency for an event of fixed magnitude, or changes in magnitude for an event of fixed frequency; though the two are in fact equivalent (Otto et al. 2012; Easterling et al. 2016). The ability to focus either on changes in frequency or changes in magnitude allows researchers to tailor their investigations to the specific requirements of different communities and practitioners (Stone et al. 2021b). Although many analyses in event attribution have focused on probabilistic approaches, information about changes in an event's severity may instead be preferred. In these cases, more mechanistic approaches — explicitly linking the changes in magnitude of a weather event with the impacts in a social or natural system — usually provide a more applicable evidential basis for decision makers (Wehner and Sampson 2021; Perkins-Kirkpatrick et al. 2022). As originally posited by Allen (2003), event attribution has also been examined in the context of litigation action against fossil fuel companies by quantifying attributable damages (Burger et al. 2020). This line of reasoning continues to be developed (Marjanac and Patton 2018), although methodological challenges remain (Skeie et al. 2017; Harrington and Otto 2019).

Event attribution studies not only quantify the extent to which a changing climate made extreme events more likely to occur, but also when *no* climate change signal exists. The latter is equally informative for decision makers: indicating which events are not harbingers of an even worse future can help to simplify and strengthen wider efforts to reduce exposure and vulnerability to subsequent events (Otto et al. 2020).

The number of published event attribution studies increased rapidly in recent years, accompanied by ongoing improvements in the quality and resolution of the climate models used, the ensemble sizes considered, and the methods employed. Most studies preserve the core framework developed for the 2004 analysis: quantifying whether and to what extent an observed extreme event was more likely to occur in today's climate, relative to a counterfactual world without anthropogenic greenhouse gas emissions. As global temperatures continue to rise at record-breaking rates (Leach et al. 2018), a framework that contextualises the present day against a pre-industrial climate remains relevant to questions of causation and responsibility, but becomes less and less relevant to adaptation decisions (Boran and Heath 2016).

Communities do not adapt relative to a fixed pre-industrial baseline. Rather, they iteratively adapt to the climate as it changes, continually integrating new sources of knowledge and evaluating the efficacy of past efforts to enhance resilience (Conway and Vincent 2021). While recognising that some systems (like population health) can iteratively adapt to worsening weather extremes more easily than others (like stormwater infrastructure), we argue that a valuable new information stream could be generated if researchers quantify the rate of change at which extreme events are happening. As discussed elsewhere (Otto et al. 2018), this gives planners an opportunity to consider not only the distance from an unfamiliar pre-industrial climate, but also the velocity of change and whether current adaptation measures would likely be robust to a warmer climate.

1 Impactful heatwaves will become effectively attributable to anthropogenic climate change

Attribution studies have been crucial in demonstrating that, due to climate change, the properties of heatwaves are worsening many times faster than any other type of extreme weather (Vautard et al. 2020). At the same time, there are questions within the research community

as to whether an extreme event can ever be fully attributable to human influences. For example, peer-reviewed analyses have shown that the probability of recently observed heatwave anomalies occurring in a modelled counterfactual world was infinitesimally small (Vogel et al. 2019; Perkins-Kirkpatrick et al. 2019), or equivalently claimed that the fraction of attributable risk for a recently observed heatwave was already effectively one, such that the “entire event” could be attributed to climate change (Imada et al. 2019).

Notwithstanding its limitations as an attribution metric discussed elsewhere (Perkins-Kirkpatrick et al. 2022), there are three reasons why we can expect estimates of the fraction of attributable risk to approach the “effectively one” category for *impactful* heatwaves within the next decade, thereby rendering its calculation increasingly redundant. First, the severity (or rarity) of future heatwaves that generate detectable societal impacts, triggering an attribution analysis (Philip et al. 2020), will be more extreme than an equally impactful event in today’s climate. This is because adaptation — both autonomous and planned — has already occurred in response to frequently recurring extremes (Fouillet et al. 2008; Barreca et al. 2016; Sheridan and Allen 2018; Achebak et al. 2019), thereby reducing the impacts associated with today’s ‘moderately severe’ events. Second, the fraction of attributable risk increases more rapidly for these more extreme event thresholds, as an artefact of the shape of statistical distributions related to extreme heat (Harrington and Otto 2018a). And third, multiple lines of evidence demonstrate that the distribution of temperatures have shifted so dramatically after only one degree of global warming (Hawkins et al. 2020), there will likely be no analogues for future heat extremes in the temperature distributions of a pre-industrial climate for many land regions of the world.

Thus, specifically resolving whether a recent heatwave — say, one which occurs once per decade in today’s climate — would have occurred either once in 100 generations or once in 1000 generations in a pre-industrial climate, is no longer useful. When the current climate has changed so significantly that the pre-industrial world becomes a poor basis of comparison, other tools are needed to instead quantify future changes in exposure or the effectiveness of adaptation to changes in extreme weather seen over recent decades.

2 The fraction of adaptable risk

Epidemiological studies in several high-income regions have detected robust reductions in heat-related mortality over the last century (Sheridan and Allen 2018), despite concurrent increases in global temperatures and in the severity and frequency of heatwaves (Li et al. 2018). While some of these reductions can be attributed to deliberate intervention strategies, like the increased use of air conditioning (Barreca et al. 2016) or the introduction of heatwave action plans (Fouillet et al. 2008; Toloo et al. 2013), part of the observed adaptation to extreme heat also appears to be a physiological response to the recurrent experience of similar temperatures (Hondula et al. 2015; Gasparrini et al. 2016; Tobías et al. 2017; Moore et al. 2019; Achebak et al. 2019).

Despite these responses, the numbers of heat-related deaths remain high: over 500 excess deaths were recorded in British Columbia in the days following a severe heatwave in June 2021 (Schiermeier 2021), while more than 2500 people died in the UK due to extreme heat in 2020 (Public Health England 2020). The numbers of heat-related deaths are poorly estimated in low- and middle-income countries (Harrington and Otto 2020), but are likely to be significant (Green et al. 2019) and unlikely to be decreasing, given recent trends of

urbanization and informal settlement growth (Pasquini et al. 2020) as well as the limited implementation of heatwave action plans.

These examples highlight that few communities worldwide are optimally adapted to the present-day climate, further validating concerns over the impacts expected with another half-degree of warming and beyond (Ebi et al. 2021). The extent of the challenges was highlighted by analyses for Stockholm, Sweden, that suggested maintaining the current number of heat-related deaths in the 2050s under RCP4.5 would require a 75% reduction in the vulnerability of adults over the age of 75 years (Åström et al. 2017). Ramping up monitoring of progress in heat-related adaptation is thus urgently needed to ensure that policies and measures are commensurate with the risks.

3 Reframing the future

Alongside mechanistic approaches, probabilistic attribution science offers a framework to compare changes in extreme weather between two scenarios, where these scenarios can differ either in the climate or in the risk profiles of those exposed to such extremes. As Box 1 explores, expanding the more versatile elements of attribution science can thus provide information relevant to today's adaptation decisions.

Box 1 Pathways to integrate attribution science with heatwave adaptation

1) Understanding rates of change

Interdisciplinary research efforts are needed to quantify precisely how the heat-related risks of another half-degree rise in global temperatures will compare with the most recent half-degree of warming already experienced, including what differences might be expected across and within regions, and how these impacts might depend on the speed with which that warming takes place (Leach et al. 2018; King et al. 2020). For example, if the relative impacts of each additional heatwave reduces faster in high-income countries with a greater capacity to adapt, then the collective epicentre of attributable heat stress impacts may shift further towards lower income countries over the coming decades. However, the speed of such a shift will depend heavily on the relative rates of change in local heatwave frequency and intensity

2) Quantifying climate change signals at the sub-city scale

Richer collaborations are needed between urban climatologists and attribution scientists to resolve heatwave attribution statements at the sub-city scale. The urgency of such efforts are strengthened by recent evidence from the United States, showing communities of colour are disproportionately susceptible to the health impacts of extreme heat, while also experiencing the largest amplification from urban heat island (UHI) effects during extreme heatwaves (Hsu et al. 2021; Witze 2021). Anomalous UHI exposure is also commonplace for low-income communities in other cities around the world (Witze 2021), but these dimensions of heatwave impact inequality have yet to be explored through an attribution lens

3) Human-centred counterfactual scenarios

While most attribution studies use counterfactual scenarios that consider hazards in a climate with anthropogenic greenhouse gas emissions removed, some examples have disaggregated the value of specific adaptation measures—like land radiative management interventions, including painting roofs white (Seneviratne et al. 2018). Another analysis quantified the implications of regions with faster-emerging signals of climate change also exhibiting higher rates of population growth in the future (Harrington and Otto 2018b)

More counterfactual scenarios like these are needed, both to decompose the added value of different adaptation policies as well as to probabilistically examine which options better reduce heatwave impacts in different settings. This could include whether certain adaptation measures alleviate extreme heat differently in humid versus arid climates, or when comparing urban and rural communities and their associated microclimates

4) Defining ‘events’ to resolve adaptation limits

Heatwaves can place electricity networks under immense strain (Stone et al. 2021a), with blackout risks particularly high in countries where energy demand for cooling can overwhelm less reliable infrastructure networks. By identifying the severity of extreme heat required for power failures to take place in different cities of the world, attribution analyses could then quantify how the probability of exceeding this threshold will change under future warming scenarios. This would help to resolve the likelihood of adaptation mechanisms failing in future and what further interventions might be needed by decision makers in response

Although relevant from mitigation and science communication perspectives, the fact that the most severe heatwaves of the near future will likely have not occurred in a pre-industrial climate is of little consequence for the purposes of future risk management. Of greater urgency is whether the rates of worsening heatwave severity can be met by equal rates of adaptation, and what upper limits — physiological, societal or otherwise — might inhibit the ability of communities to prepare for the unknown climates of the future. The tools that demonstrate climate change can affect extreme weather today now need expanding to answer the questions of tomorrow.

Author contribution LJH conceived the study. LJH, KLE, DJF and FO all contributed equally to the writing of the manuscript.

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Data availability Not applicable.

Declarations

Ethics approval and consent to participate LJH, KLE, DJF and FO all declare their consent.

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