Legal liability for climate change impacts: strengthening the scientific basis



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Abstract

The courts have become an increasingly important venue for efforts to combat the impacts of climate change. Claims have brought on a range of legal grounds, but many climate lawsuits are based on the existence of a causal relationship between emissions of greenhouse gases and impacts that occur as a result. Such claims may be made to establish emitters' liability for climate change impacts, or to demonstrate that contributions to climate change cause harm, and therefore that greenhouse gas emissions should be curbed.

Establishing causation in climate litigation requires synthesis of climate science and legal arguments. This thesis evaluates how legal arguments can align with developments in climate change attribution science, a subfield of climate science that can assess the contribution of anthropogenic influence to climate-related impacts. It then considers how attribution-science evidence has been used in past lawsuits, and responds to emerging scientific questions regarding the effects of climate change that have arisen in the courts.

Legal scholars have identified attribution science as holding the potential to establish causation in the courts, but the analyses described in section 4 of this thesis found that the evidence presented in climate lawsuits often lags developments in climate science and that, in some cases, this may have hindered findings of specific causal relationships between greenhouse gases and their consequences. Responding to these findings, sections 5 and 6 report analyses that advance the state of knowledge in areas of attribution science that hold particular legal relevance.

Section 5 studied anthropogenic influence on the glacial lake outburst flood hazard from Laguna Palcacocha in the Peruvian Andes, in the context of ongoing litigation (*Lliuya v. RWE*). It concluded that 85-105% (5-95% confidence interval) of the observed industrial-era warming in the region surrounding Laguna Palcacocha was attributable to anthropogenic climate change and that the overall retreat of the Palcaraju glacier since 1880 is entirely attributable to this warming. Moreover, it is virtually certain (>99% probability) that the observed glacier retreat cannot be explained by natural variability alone. Laguna Palcacocha

has expanded in the wake of this glacier retreat, substantially increasing the outburst flood hazard to the downstream city of Huaraz.

Finally, this thesis responds to the increased use of human rights-based arguments in climate litigation and develops methods that extend attribution science analyses from quantifying the effect of climate change on physical hazards to their impacts on health. These methods address limitations in existing approaches, including the representation of the climate-health relationship, choices in calculating counterfactual temperatures, differing approaches for assessing long-term trends and individual events, and estimating the effects of adaptation. The approach described in this section is then applied to quantify heat-related mortality attributable to climate change in the Canton of Zürich (Switzerland) over 1969-2018. We found a substantial burden of heat-related mortality attributable to climate change both within and outside of heatwaves. Overall, 1,7000 heat-related deaths were attributed to climate change, and adaptation was found to have avoided at least a further 700 deaths.

The thesis spans climate science, glaciology, epidemiology, and legal analysis. Altogether, this research explains how science can strengthen legal causation arguments in climate litigation, and develops methods and analyses to this end. Scientific evidence has a central role to play in developing well-grounded climate lawsuits, and methodological developments can resolve questions raised in court.

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1 Introduction

In 1941 a devastating flood swept through the Andean city of Huaraz (Peru), killing at least 1,800 inhabitants.[1] The 'glacial lake outburst flood' occurred as the natural dam that retained Laguna Palcacocha failed, releasing a torrent of water and sediment down the Cojup valley and onto the city.[2] Recent research suggested that this mid-20th Century disaster may have been an early impact of human-caused climate change, as the glaciers at the head of Laguna Palcacocha retreated from their pre-industrial positions, allowing the lake to swell in the wake of their retreat.[3]

Since the mid-20th Century, climate change has forced the Palcaraju and Pucaranra glaciers to recede a kilometre further uphill.[3] In place of these glaciers, Laguna Palcacocha has expanded 34-fold in volume[4] and once again threatens to flood the city of Huaraz, now a city of 140,000 people.[5,6] In response, the local authorities are planning to build enhanced hazard-reduction measures at the lake. To recover part of the costs of doing so, a local resident filed a lawsuit in the District Court in Essen (Germany).* In the claim, Saúl Luciano Lliuya sought compensation for the pro rata cost of measures taken to protect his property against the flood hazard from RWE, a German energy company and Europe's largest emitter of carbon dioxide,† based on Article 1004 of the German Civil Code, which concerns liability for nuisance.

In the lawsuit, Lliuya claims that climate change caused the increased flood risk that Huaraz faces today, and that RWE's contribution to historical greenhouse gas emissions – estimated to be 0.47% of all human-caused emissions[7] – renders them partially responsible for the costs of the flood prevention measures. Applying a proportional approach to allocating contributions to total damages, the claim seeks 0.47% of these costs as compensation from

* The case is now on appeal at the Higher Regional Court of Hamm.

† As of 2021, scope 1 emissions only. See https://www.greenpeace.de/publikationen/kurzanalyse_rwe_-_vom_winde_verweht_maerz_2021.pdf [accessed 20.06.2022].

RWE. The case was initially dismissed by the District Court of Essen on the grounds that the high number of contributors to climate change prohibits the attribution of damages to individual entities.[*] However, the Higher Regional Count of Hamm accepted that the case was conclusively argued on appeal and initiated an evidentiary phase in which it would evaluate two scientific questions: first, whether it is indeed the case that the claimant's property is threatened by the potential flood; and second, whether a causal link can be established between RWE's emissions and the heightened flood risk.[†]

Lliuya v. RWE is just one of over 2,000 cases brought before courts worldwide on matters related to climate change (as of June 2022), and the number of lawsuits and other legal interventions on climate change have grown dramatically in the last decade.[8] Climate litigation is a diverse field of practice and the objectives and strategies of those bringing legal actions vary substantially. These cases include claims seeking to reduce greenhouse gas emissions by enforcing or strengthening state or corporate[‡] emission-reduction commitments and policies on constitutional,[§] administrative,[**] human-rights,[††] and tort[‡‡] law grounds. Other cases have sought to challenge permitting, financing, construction and operation of high-emitting assets, corporations'[§§] and their directors'[***] inadequate management or

[*] Lliuya v. RWE AG District Court of Essen Judgment of 15 December 2016—2 O 285/15.

[†] Lliuya v RWE AG (Az 5 U 15/17 OLG Hamm). At the time of writing, the case is pending and the court and its appointed experts recently completed a site visit to Laguna Palcacocha in Peru.

[‡] *Milieudefensie et al. v. Royal Dutch Shell plc.*

[§] *Neubauer et al. v. Germany*

[**] *R (oao Friends of the Earth) v. Secretary of State for Business, Energy and Industrial Strategy*

[††] *Paul Pabai & Guy Paul Kabai v. Commonwealth of Australia*

[‡‡] *Urgenda v. State of the Netherlands*

[§§] *People of the State of New York v. Exxon Mobil Corp.*

[***] *ClientEarth v. Board of Directors of Shell*

disclosure of financial risks, interpretation of fiduciary duties, poor due diligence,[*] and deliberate misinformation.

Climate lawsuits are typically brought in response to (perceived) governance gaps; accordingly, they may challenge policies that contravene the rights of future generations,[†] fail to address the needs of vulnerable groups,[‡] fall short of international-law or human-rights obligations,[§] are not self-consistent, for instance by being incommensurate with other legal duties and targets,[**] or contravene domestic-law or international obligations.[††] Further claims have been brought in response to the non-provision of recourse for individuals or communities suffering disproportionate impacts of climate change.[‡‡]

Climate-related legal action can also bridge the gap between policies introduced at the international level and the duties of individual states or corporations in contributing to the objectives of those policies. Cases of this type include claims brought against states and corporations, in which courts have been asked to interpret the 2015 Paris Agreement as conferring legal duties on defendants.[§§] The Paris Agreement is an outcome of over two decades of international negotiations on climate change and commits states to contributing to global goals on mitigation of, and adaptation to, the impacts of climate change. However, gaps between the wording and implementation of the Agreement are substantial, and a growing target of legal action. One such example is the robustness and integrity of domestic[9]

[*] *Envol Vert et al. v. Casino*

[†] E.g., *Neubauer et al. v. Germany; Future Generations v. Ministry of the Environment and Others*.

[‡] E.g., *Mex M v. Austria*.

[§] E.g., *Urgenda Foundation v. State of the Netherlands*; *Milieudefensie et al. v. Royal Dutch Shell plc.*, *R (oao Friends of the Earth) v Secretary of State for Business Energy and Industrial Strategy*.

[**] E.g., *ClientEarth v. UK, ClientEarth v. PGE*.

[††] E.g., *Save Lamu v. NEMA*, *Plan B v. Secretary of State for Transport*.

[‡‡] E.g., *Lliuya v. RWE*, *Four Islanders of Pari v. Holcim*.

[§§] See, for instance, *Milieudefensie et al. v. Royal Dutch Shell plc., Waratah Coal Pty Ltd v Youth Verdict Ltd & Ors (No 6) [2022] QLC 21, Ecodefense & Other NGOs v. Russia.*

and corporate[10,11] emission-reduction policies, which are largely insufficient to meet the objectives of the Paris Agreement. Moreover, even when state and corporate climate targets appear to be adequate, their lack of credibility and legal enforceability are subject to growing critique.[11]

The Paris Agreement also set a thus-far unmet floor of USD 100 bn in annual finance to support mitigation and adaptation measures in developing states,[12] reaffirming a target set in the 2010 Cancun Agreements.[13] However, the Paris Agreement provides no basis for financial compensation for climate-change impacts: the pre-amble to the Agreement states that the Parties '[agree] that Article 8 of the Agreement [which concerns loss and damage] does not involve or provide a basis for any liability or compensation'.[12] Despite the establishment of a new loss and damage fund at COP27,[14] it is not known yet to what extent this will deliver meaningful finance to communities affected by the impacts of climate change.

The non-provision of a mechanism for compensation and the continued inadequacy of mitigation effort constitutes two major gaps in climate governance. Across jurisdictions, activist lawyers, NGOs, local and national governments have sought to address these governance gaps (among others) through the courts in growing numbers of lawsuits.[8]

In many cases related to climate change, climate science has a central role to play: *Lliuya v. RWE* is an exemplar of this. In climate lawsuits, legal concepts such as human rights, torts, nuisance, and constitutional duties are invoked, with scientific evidence used to show how pre-existing legal theories can be applied in the context of climate change. The specific types of evidence needed to support claims varies between cases. In growing numbers of claims, claimants have referred to scientific findings that attribute existing impacts to greenhouse gas emissions, and projections of future impacts that would occur in response to past and future emissions. These findings can be used to demonstrate that defendants' actions interfere with rights of claimants. Other branches of climate research are cited too. For instance, some cases

challenged the approval of individual high-emitting projects, such as coal mines,[*] or entire climate targets or policies.[†] In these instances, courts have accepted evidence of greenhouse gas mitigation pathways or carbon budgets aligned with specific temperature goals in finding projects and targets misaligned with the Paris Agreement or falling short of other legal duties.

The diversity of cases filed to date creates varying needs for scientific input. This thesis focuses on climate change impact science, and attribution science in particular. These types of scientific insight can be used to evaluate legal claims that causal relationships exist between emissions of greenhouse gases and their impacts. Existing literature detailed the role that attribution science can play in improving the prospects of causal arguments in climate lawsuits.[15–22]

2 Thesis outline

The research described in this thesis spans law, climate science, glaciology, and epidemiology. These apparently disparate areas of research are brought together here in answer to a single question: how can science support legal claims of causation between greenhouse gas emissions and their impacts in climate lawsuits? To begin to answer this question, the role that climate change attribution science can play in litigation is detailed. Section 3 explains how attribution-science evidence can be leveraged in support of climate-related claims. Specifically, this section briefly overviews the state of attribution science and explores how characteristics of the science may affect its legal interpretation.

Section 4 builds on this introduction and analyses existing case law related to climate change impacts, including the scientific facts introduced by parties to the case and judicial interpretation of these facts (paper 1). In assessing ongoing issues in the application of climate change attribution science in the context of litigation, this thesis identifies a general lack of

[*] E.g., *Gloucester Resources Limited v Minister for Planning* (2019) 234 LGERA 257; [2019] NSWLEC 7, *Waratah Coal Pty Ltd v Youth Verdict Ltd & Ors* (No 6) [2022] QLC 21.

[†] E.g., *Milieudefensie v Royal Dutch Shell* [2021] District Court of the Hague ECLR:NL:RBDHA:2021:5339

use of specific attribution science evidence in climate lawsuits. This raises the question of how the availability and use of such evidence might affect legal outcomes. This thesis identifies and addresses litigation-relevant knowledge and methodological gaps. Altogether, the thesis provides a bridge between law and climate science by identifying and addressing key gaps in litigation-relevant scientific research that could improve the prospects of litigation concerning the impacts of climate change.

Paper 2 (section 5) responds to the initiation of an evidentiary stage in *Lliuya v. RWE*, in the Regional Court of Hamm, Germany. *Inter alia*, the court sought evidence evaluating the alleged causal link between the greenhouse gas emissions of the defendant and the increasing flood hazard from Laguna Palcacocha, a proglacial lake in the Peruvian Andes. In this context, my co-authors and I conducted an attribution study for the evolving glacial lake outburst flood hazard from this lake. This study developed an original approach for attributing the hazard of an outburst flood to climate change and synthesises methods from climate science, glaciology and mountain hazard assessment.

Finally, as climate litigation has increasingly employed human rights arguments,[23] understanding the effects of climate change on human health has taken on heightened importance. Paper 3 responds to this demand, and provides a novel methodological framework for evaluating health impacts attributable to anthropogenic climate change. In this paper, my co-authors and I applied these methods to quantify heat-related mortality attributable to climate change in the Canton of Zürich (Switzerland) over the period 1969-2018. We also detailed and addressed limitations in existing methods for attributing health impacts to climate change. The advances of the approach described in this article facilitate accurate quantification heat-related deaths attributable to climate change in absolute terms.

While the methods described are salient for climate lawsuits brought on human rights grounds, our analysis provides specific insight in the context of *KlimaSeniorinnen v. Switzerland*, a case recently relinquished to the Grand Chamber of the European Court of Human Rights. In this case, plaintiffs argue that unabated climate change increases their exposure to health risks associated with heatwaves. One point of contention in the legal

proceedings is whether existing climate change should already be considered to be 'dangerous'. To resolve this issue, evidence of the past and ongoing impacts of climate change on heat-related mortality and morbidity in Switzerland is highly pertinent.

3 Attribution science and legal liability for climate change impacts

Climate change is already causing substantial humanitarian and economic harm worldwide, and its impacts disproportionately affect vulnerable communities that have contributed among the least to historical greenhouse gas emissions.[24] Procedural practicalities notwithstanding, the moral argument for a legal response to the inequitable distribution between harmful actions and harms experienced appears clear: a governance gap exists that excludes those affected by climate change impacts through little fault of their own from receiving compensation from those causing these impacts.

The short history of efforts to apply tort, public nuisance, trespass, consumer protection and other laws to obtain compensation for climate change impacts has not yet led to pay-outs.[25] Extant literature on the topic identifies various obstacles. In part, these challenges have arisen because the nature of climate change is unlike many other forms of legal interference. Firstly, the impacts of climate change, while experienced unequally, affect everyone to a greater or lesser extent. In some jurisdictions, plaintiffs must have suffered losses that are different in kind or degree to those affecting the general public to have standing, which may introduce obstacles given the widely distributed nature of climate change impacts. Secondly, climate change impacts result from the combined actions of all greenhouse gas emitters and so challenges exist in delineating a legal line between those entities that may be held liable for impacts (a 'defendant class'), and those who cannot.[16]

Finally, there is the challenge of proving causation, about which this thesis is primarily concerned. The general causal relationship between greenhouse gas emissions, rising global temperatures, and the manifestations of climate change in a range of impacts is widely established in the scientific literature, including in successive reports of the Intergovernmental Panel on Climate Change (IPCC). Such causal relationships have been

recognised by courts in past climate lawsuits.[21] A greater hurdle for establishing causation in court is the issue of specific causation: whether the emissions of an individual entity can be said to have contributed to the losses suffered by the plaintiff. The existing body of cases seeking compensation for climate-related harms have rarely proceeded to the merits stage.* Nevertheless, the issue of establishing specific causation has posed an obstacle to meeting admissibility requirements in existing lawsuits,[21] and is considered to present a substantial challenge when cases proceed beyond the admissibility stage.[16,26] These specific causation claims can be addressed – and potentially, in conjunction with legal reasoning, resolved – by a sub-field of climate science known as 'attribution science'.

3.1 The state of the art in climate change attribution science

Climate science has advanced substantially in recent decades. Even in recent years, news coverage of extreme weather events would state that no individual event could be shown to be the result of climate change. Similar claims have been made in legal arguments and judgements.[21] This no longer reflects the state of the science. It is now possible to conclusively demonstrate the influence of climate change on many impacts occurring worldwide,[27] including individual heatwaves or storms, or the retreat of glaciers. A growing literature links these physical impacts to their health,[28] social, and economic[29] consequences. Recent studies have also linked the emissions of countries, companies, and individuals with a range of climate change impacts, including global-temperature and sea-level rise,[30,31] ocean acidification[32], and heatwaves.[33–35] Attribution studies can now span the full causal chain from the greenhouse gas emissions of individual entities, through to the physical impacts of these emissions, and the societal impacts that result.[36]

Attribution science is a subfield of climate science that assesses the contributions of greenhouse gas emissions to climate-related harms. In this way, attribution science provides a means of evaluating claims of specific causation in climate litigation. Within attribution

* With the notable exception of *Lliuya v. RWE*, in which the Regional Court of Hamm initiated an evidentiary phase in 2017, which remains pending at the time of writing.

science, one can distinguish between a series of subcategories. 'Source attribution' assesses the historical and ongoing greenhouse gas emission contributions of individual emitters, typically (though not necessarily) corporations or countries.[7] 'Climate change attribution' evaluates the effects of human activity and other drivers of climate change on components of the earth system. Typically, such studies comprise two high-level components: 'detection' and 'attribution'. In 'detection', an observed trend is evaluated to assess whether it exhibits statistically significant difference to natural internal climate variability. 'Attribution' then evaluates the consistency of detected changes with those expected to result from internal and external forcings, including the effects of anthropogenic influence on the climate, and the inconsistency of these changes with climate change scenarios that exclude the effects of important forcings.[37] Although the attribution of extreme meteorological events is sometimes allocated to a separate category, here I use the term 'climate change attribution' to include studies that evaluate the relationship between greenhouse gas and aerosol emissions and the physical consequences of these emissions, including global temperature change, sea-level rise, extreme weather events and glacier retreat. Finally, 'impact attribution' has been used to describe the link between physical processes and their societal, economic, environmental, or humanitarian consequences.[15] Individual studies commonly evaluate only one of these three types of attribution, although recent studies have extended analyses to synthesise different components of attribution.[30,35,38] Section 6 (paper 3) of this thesis refines approaches for extending attribution studies to the health impacts of climate change.

Counterfactual analyses lie at the heart of attribution science, although the precise nature of these assessments differ between studies of extreme weather events and slow-onset processes. Slow-onset processes describe natural systems that respond gradually to climate change and are insensitive to short-term climatic variations. Detection and attribution studies of such changes have evaluated the influence of climate change on glacier retreat[3,39] and melt,[40] sea-level rise,[31,41] mean lake temperatures,[42] and regional temperature change.[43] These studies typically assess the probability that an observed change can be explained by natural factors

alone or calculate the contributions of anthropogenic and natural factors to the observed change.

In parallel with these developments, methods for extreme-event attribution studies have been developed to assess human influence on individual meteorological events, including storms, droughts, heatwaves, and floods.[44] Extreme-event attribution studies may use observations and climate models to simulate how frequently events of at least a threshold intensity would be expected to occur in the present climate and in a counterfactual climate without human greenhouse gas or aerosol emissions. Accordingly, the effect of human influence on the probability of such events can be quantified. The same methods can also assess the attributable change in the magnitude of an event of given probability. For instance, in a study of the June 2019 heatwave in France, Vautard et al. (2020) found that the probability of a heatwave occurring with temperatures at least as hot as those observed had increased by 180 times as a result of anthropogenic climate change. Alternatively, using the intensity-based framing, the same study found that had a heatwave of equal probability occurred in the climate of 1901, temperatures would have been 4 °C lower.[45] Extreme event attribution studies often present results for both formulations of the findings.[46] The differing interpretation of these two framings of attribution results is discussed in detail in section 6. Recent developments in the attribution of extreme weather events to climate change have included the application of high-resolution forecast models to overcome limitations in the ability of lower-resolution General Circulation Models (GCMs) or Regional Climate Models (RCMs) to simulate specific meteorological phenomena.[47]

A conceptually distinct but complementary approach to attribution has also been developed, known as the 'storyline approach'. Rather than quantifying attributable changes in event probabilities, the storyline approach focusses on the physical dynamics or state of the atmospheric circulation that led to the unfolding of a specific climate-related event. The question asked by this approach is: '*given the way event the event in question unfolded, how was this influenced by climate change?*'. As such the storyline approach assesses the effect of climate change on an event conditional on its dynamics and anthropogenic influence on atmospheric

conditions are not detectable by this approach.[48] Instead, attribution studies applying the storyline approach focus on how the effects of these dynamical conditions were altered due to human-induced changes to atmospheric thermodynamics.

Answers provided by the storyline approach are more explanatory than statistical in linking causal factors to the magnitude or impact of an event. They may find, for example that natural variability was responsible for 50% of the magnitude of a given event, conditioned on the dynamical context of the observed event.[49,50] In a recent article, Lloyd & Shepherd discuss how the storyline approach could be aligned with legal reasoning on causation.[50]

In this thesis, separate attribution analyses are conducted for glacier retreat and heat-related mortality. Sections 3.1.1 and 3.1.2 provide brief overviews of key literature in this area that provide context for the research described in subsequent sections. A more complete description of methods and literature can be found in sections 5 and 6.

3.1.1 Attributing glacier retreat to climate change

The retreat of mountain glaciers is widely regarded as being emblematic of the effects of climate change, and for good reason. Mountain glacier lengths respond to climatic perturbations over multi-decadal timescales, and consequently act as lowpass filters of climate variability:[51] sensitive to long-term climate trends, that have been conclusively attributed to anthropogenic climate influence,[52] and relatively insensitive to short-term fluctuations. Nevertheless, the first major assessment of anthropogenic influence on global glacier mass loss found that only 25% (±35%) of mass loss over 1851-2010 was attributable to human influence.[53] This study was superseded by Roe, Christian, & Marzeion (2021)[40] which challenged the assessment in ref. [53] and found that the central estimate of glacier-mass loss attributable to human influence on the climate since 1850 was 100% (85-130%, *likely* uncertainty range for alpine glaciers; 85-180% *likely* uncertainty range for larger ice caps due to their longer response times).

The results of Roe, Christian, & Marzeion differ to the earlier assessment of Marzeion et al. for two main reasons. Firstly, Marzeion et al. (2014) overestimated glacier response times to

climate change, increasing the influence of climate conditions prior to the onset of anthropogenic influence and the degree of glacier disequilibrium with the climate in the mid-19th Century. Secondly, Marzeion et al. assumed that mass balance of all glaciers had been in equilibrium at a point in the past estimated based on sparse observations of historical glacier mass balance; in practice, the time at which a glacier had been in mass balance is heavily influenced by the glacier's response time, which can be estimated as the ratio between the ice thickness and (negative) terminus mass balance.[51] These characteristics vary substantially between glaciers. Glaciers with short response times will have been in near-equilibrium at the onset of anthropogenic warming. These findings confirm that glacier mass loss is indeed a direct consequence of human-induced climate change.

Human influence on glacier retreat has also been assessed. In 2017, Roe, Baker, & Herla evaluated 37 glaciers and found that for all but one of them, the probability that observed retreat could be explained by natural climate variability was <10% (<1% for 21 of 37 glaciers).[39] The anthropogenically-driven retreat of mountain glaciers has resulted in the formation and expansion of pro-glacial lakes across alpine regions[54] from which glacial lake outburst floods may occur. The methods applied in section 5 of this thesis build on these findings.

3.1.2 Attributing health impacts to climate change

Human-induced climate change is causing morbidity and mortality from increasingly frequent and intense extreme weather events, rising mean temperatures and sea levels, and altering seasonality.[55,56] While largely unquantified,[57,58] these changes are expected to have direct physiological effects, shifting the distribution of pathogens and disease vectors, compromising food crops, and affecting the socioeconomic determinants of health.

Anthropogenic climate change has increased dengue and Lyme disease incidence;[59] caused injuries, death, and mental ill-health resulting from increasingly frequent and intense storms[60] and rising ambient temperatures;[61] and increased the prevalence of undernutrition following more frequent or intense droughts that disrupted rain-fed agriculture.[62] The impacts on

undernutrition are augmented by the direct effects of rising atmospheric carbon dioxide concentrations that reduce the protein, micronutrient, and vitamin content of key nutrition sources, particularly wheat and rice.[63,64] Climate change also increases wildfire incidence in some regions[65] and mortality and morbidity attributed to wildfire-induced PM2.5 pollution[66]. Existing detection and attribution assessments do not capture the full extent of the impacts of climate change on health. As global temperatures continue to rise, the magnitude of associated health impacts is projected to increase further.[67–69]

Understanding and accurately modelling the impacts of climate change on health may require improved understanding of the physiological, as well as statistical, relationship between climate drivers and their health consequences. Ongoing debates in the literature concern the use of location-specific predictors of climate-health relationships to conduct analyses in data-limited locations,[70] the effect of humidity on heat-related mortality and ill-health,[71] and the effect of climate change on winter mortality as winter temperatures are moderated in mid-to-high latitude regions.* In some cases, epidemiological analyses yielded contrasting results to those expected based on physiological understanding.[72] Despite these ongoing debates, parallel developments in methods for attributing health impacts to climate conditions and climate conditions to anthropogenic influence have generated the potential for robust assessments of the impacts of climate change on health. These developments are discussed in further detail in section 6 and raise the question of how best to synthesise epidemiological and climate-science methods.

Policy responses to manage the health impacts of climate change remain relatively limited[73]. Well-communicated attribution research may support various applications, including as a

* The overall impact of climate change on temperature-related mortality may also include warmer winters that could counteract some of the increase in heat-related mortality.[56] However, there is a lack of agreement in academic literature on the mortality impacts of increasing winter temperatures.[56] Previous assessments found that winter mortality is only weakly associated with temperature and so unlikely to be substantially reduced by warming[250] and recent studies found increases in cold-attributable deaths despite warming winter temperatures due to population ageing.[201] Under projections of continued population aging, cold-related mortality is likely to remain substantial.[251]

source of evidence for climate lawsuits[18] (see section 4), supporting the development or assessing the impact of adaptation strategies,[74] and informing negotiations on loss and damage associated with climate change.

3.2 Considerations for using attribution science in court

Parties to climate lawsuits are in the unusual position of not only being able to support claims with a large body of scientific research on climate change and its impacts, but also being able to draw on the findings of the IPCC. The IPCC's reports synthesise the scientific community's consensus understanding of climate change. Since IPCC reports undergo a process of government review and approval, they are an assessment of the state of the science that is accepted by all governments and are therefore considered authoritative in court.

As such, IPCC reports are highly valuable sources of evidence, and their findings are widely considered to be of near-unimpeachable credibility. The IPCC's assessments cover a wide range of topics including projections of future climate change impacts, attribution of observed climate change, and mitigation pathways consistent with limiting global warming to various levels. The IPCC reports do not provide new assessments but review existing literature and draw global and regional conclusions based on published research. For instance, the Working Group I contribution to the IPCC's Sixth Assessment Report, published in 2021, assessed regional changes in hot and cold extremes, heavy precipitation and three different types of drought. The report also provided an assessment of the confidence in the human contribution to these observed changes, grounded in the attribution science literature (see Figure SPM.3 for a summary and section 11.9 in chapter 11 for further details).[52] IPCC reports also provide location-specific examples and case studies derived from peer-reviewed literature. However, these examples are not comprehensive and conclusions are typically drawn on global or regional scales. As noted above, regional-scale assessments are of particular use for supporting findings of general causation.

IPCC reports' findings on attribution of climate change impacts provide a robust general basis for causal claims. However, these reports may not be sufficient to support findings for

specific causation if they do not provide assessments of the role of anthropogenic greenhouse gas emissions in causing the individual impacts that result in a claimant's losses, although they may cite papers that do. Similarly, government climate reports may summarise findings from a range of other sources to produce national or sub-national scale assessments, but depending on the nature of the impact, they may also not provide information at the level of granularity needed for specific causation. IPCC and other assessments therefore have a crucial role to play in providing a scientific basis for causal claims and can lend credibility to more specific claims – providing a 'distinct causal field' in the context of which specific causation can be evaluated[22] – but they are not usually sufficient to establish legal causation in an individual case. This underlines the ongoing importance of dedicated attribution studies for supporting specific causal claims in climate litigation.

The availability of attribution-science evidence to support legal arguments has rightly been recognised as an important development. Attribution methods may increase the likelihood that courts will find a causal relationship between greenhouse gas emissions and climate change impacts. However, the application of this evidence to establish causation is subject to several considerations. Here, I briefly explore the scientific understanding and legal implications of (1) the non-exclusive contribution of human influence to extreme events, (2) the assumption that greenhouse gases are fungible in their contribution to climate change impacts, which underlies the use of market share theory for allocating contributions to harm, (3) the existence of multiple metrics for attributing climate-related harms to human influence, and, in common with most fields of scientific inquiry, (4) the influence of methodological choices on attribution findings, and (5) uncertainty in attribution assessments. The assessment presented here builds on existing literature on legal causation.[*] I explain that these considerations are relevant for understanding how causal argumentation can be developed in legal contexts but need not be an obstacle to establishing causation in court.

[*] Note that across most common and civil law jurisdictions similar concepts of causation are applied, even though the standards of proof and precise formulation of causation tests may vary.

3.2.1 Some climate-related harms would have happened anyway

Heatwaves, storms, and droughts are not new phenomena. Such events have occurred throughout history and would have continued to do so, but, in many instances, with lower severity or frequency if not for human-induced climate change. By contrast, human-induced climate change is the main driver of observed sea-level rise[75] and the mass loss[40] and retreat of mountain glaciers has been attributed directly to human influence on the climate.[3,39] Since many slow-onset impacts would not have occurred in the absence of climate change, it has been suggested that litigation focused on such impacts would be more likely to succeed.[26]

Nevertheless, the multiplicity of contributors to climate change means that in almost all settings, it would not be possible to meet the stringency of a 'but for' test: that absent a single defendant's conduct, the claimant's losses would not have occurred.[16,19,22] Even so, existing literature on climate litigation has also indicated the viability of establishing causation through applying other causation tests for both meteorological events and slow-onset changes.[15,17,18,22] Other causation tests have been widely applied in past litigation and may involve normative correctives to the but for test. Such correctives may allow, for instance, causation to be established in circumstances where anthropogenic greenhouse gas emissions' collective contribution to impacts would have been sufficient to establish causation, with individual emitters' contributions quantified based on the proportion of historical CO_2 / CO_2e emissions for which they are responsible (an approach known as 'market share theory').[15,18]

The facts that there is an underlying chance that harmful events could have occurred in the absence of the combined activities of greenhouse gas emitters, and the numerosity of contributors to greenhouse gas emissions are not unique to climate change. Courts are well versed in assessing causal claims in settings where defendants' activities have increased, rather than created risks. In evaluating causal claims pertaining to negligence, strict liability, and the tort of nuisance, modified causation rules assess defendants' contribution to the infringement of rights. Accordingly, as is the case for those contributing to climate change,

individual defendants need only to have contributed to claimants' impacts for causation to be established.[17,22]

To assess causal claims, evidence is assessed against a 'standard of proof' that determines the strength of a scientific relationship needed for causation to be established. The standard of proof used for evaluating probabilistic causal claims is formulated differently across jurisdictions, but may in practice include a substantively similar assessment of the strength of causation evidence. It can be difficult to assess exactly how comparatively stringent thresholds for causation are across jurisdictions. However, in general, the U.S., England, Ireland, Denmark, and Lithuania adopt a 'more probable than not' standard, in which a doubling of the probability of harm is needed to establish causation. Austria and the Netherlands adopt a 'high probability' and 'reasonable degree of certainty' standard, respectively. In Germany a near certainty standard has been applied, but often judges simply need to be convinced of the existence of a causal link. Other continental European jurisdictions have adopted higher standards of proof: in Bulgaria and Spain certainty is expected, in Greece, France, Poland, and Italy a judge must be convinced that the causal link exists.[76]

3.2.2 The fungibility of greenhouse gases

Once greenhouse gases from one source are emitted, they become mixed in the atmosphere with those from other sources. The combined effect of these emissions is to raise global temperatures, which, in turn, results in regional warming and individual impacts such as changing probabilities or intensities of weather events or glacial retreat. As a consequence, it is not possible to ascertain which greenhouse gases, emitted by whom and from where resulted in a given impact: climate change impacts result from the combined contributions of all emitters. This underlies the application of market share theory, also used in tobacco and pharmaceutical litigation, as a legal approach for allocating contributions to harm. Accordingly, an entity's contribution to an impact is calculated as equal to their proportional contribution to emissions as a whole, irrespective of where or when the emissions were produced. Despite this simplification, the approach is common in contexts where losses

derive from multiple entities' actions in a linear or nonlinear fashion, because it reduces evidentiary challenges when allocating damages. For extreme weather events this approach is well supported scientifically: changes in extreme weather events evolve in step with global and regional temperature rise, and therefore near-concurrently with emissions.[77]

However, for other climate change impacts that display lagged responses to temperature change and emissions, such as sea-level rise and the retreat of mountain glaciers, this relationship is more complex. These slow-onset changes respond to climatic perturbations over a period of decades (for mountain glaciers) to centuries-to-millennia (for sea-level rise).[51,78,79] Consequently, recent emissions will only just have begun to contribute to sea-level rise, whereas greenhouse gases produced decades ago will have induced more substantial changes. While the market share approach to assessing individual entities' contributions to impacts is generally a useful approximation, for slow-onset processes, this approach may need to be adapted as the assumption that emissions are fungible is no longer strictly accurate.

In addition to the market-share approach, which is still useful for allocating contributions to impacts in a range of settings, it is also possible to quantify the contributions made by individual emitters of greenhouse gases to climate change impacts. Such studies typically assess the difference in an impact between a climate with observed greenhouse gas emissions, and a climate without the emissions of the entity in question. Alternatively, studies have quantified the effects of the contribution made by an individual emitter as compared with a natural climate without any human influence. Recent literature has linked climate change impacts to the emissions of individual corporations, states, and even individuals. These studies quantified the contributions of greenhouse gas emitters to global-mean temperature change[80], existing[30] and future[31] global sea-level rise, ocean acidification[32], and the occurrence probability of extreme weather events[33–35,81]. The findings of such studies are sensitive to framing choices for how the attribution analysis is conducted. For instance, the contribution of an individual emitter is assessed differently if it is quantified by comparing the present climate with one in which their emissions had not happened or by comparing a natural

climate with one in which only their emissions are included.[81] Further, choices need to be made regarding which emissions of a defendant should be included. Relevant considerations here include the timeframe over which defendants may be held liable for their emissions, or the emissions scopes that individual defendants can be held responsible for,[80] as is also the case for the market share theory approach.

The scientific feasibility of attributing climate impacts to individual emitters has the potential to support causal claims and demonstrate that individual emitters' contributions are measurable and non-zero. However, it has also been suggested that such advances could add to rather than simplify the challenges in establishing causation. Thomas Burman argues that studies assessing the contribution of individual emitters to climate harms may remove the option to seek more relaxed standards of causation, as these are typically granted in instances of causal uncertainty, where demonstrating which entities caused the harm would not be possible.[26] Secondly, such studies draw attention to the fact that the contributions of individual defendants can be very small. Consequently, there is the risk that lower standards of proof will be unavailable to claimants and the size of a defendant's contribution will not be sufficient for meeting stricter causation requirements.[26] It also remains the case that only in highly specific settings would one defendant's contribution be sufficient to cause impacts that would not otherwise have occurred. Such an impact might be a river that overtops its embankment, flooding a claimant's home, and for which a very small reduction in rainfall would have been sufficient for the floodwaters to be retained within the river channel. The improbability of such a specific example occurring in practice underlines the challenges to establishing a 'but for' causal link to an individual defendant in climate litigation that may be applied in some jurisdictions. However, the application of other legal concepts such as market share theory may facilitate the allocation of liability in settings where individual contributions to emissions are not large enough to themselves satisfy a 'but for' test.

The findings of attribution studies demonstrating individual emitters' contributions to climate harms are hardly surprising. Such findings are consistent with pre-existing knowledge on the (generally, proportionately small) historical contributions of individual

greenhouse gas emitters to climate change[7] combined with the assessment of the contribution of human influence as a whole to a range of climate impacts. Moreover, in some past lawsuits, courts have held that it would not be possible for claimants to demonstrate what, if any, contribution an individual defendant had made to their losses.[21] Developments in this area of research renders such statements outdated.

3.2.3 Metrics for representing human influence on climate impacts

A further set of considerations concern the presentation of attribution findings themselves. For meteorological events, as noted above, attribution studies can assess the extent to which climate change affects the likelihood of an event occurring that is greater than or equal to a given magnitude, or the attributable change in intensity of an event of given probability. The methods applied for either framing of the analysis are basically identical and attribution studies typically present both intensity and probability-based approaches to conducting the analysis.

The existence of two metrics for representing the findings of attribution studies that can indicate a qualitatively different role of climate change raises the prospect of a battle between contrasting but apparently valid assessments of the effects of greenhouse gas emissions. For instance, a recent study of a heatwave in Siberia in 2020 found that it would have been almost impossible for temperatures to have been as hot as they were if not for human influence on the climate.[82] When considering how much cooler the equal-likelihood event would have been in the absence of climate change, the study found that temperatures would have been a few degrees centigrade lower than observed in the real event: cooler, but still hot.[82] Both metrics quantify the role played by natural climate variability and anthropogenic climate forcing.

Scientifically, intensity and likelihood-based metrics are two sides of the same coin. However, the different formulations may be subject to different causation tests and not lead to the same interpretation by courts. Courts must therefore understand how these metrics relate to one another and their relative explanatory power for the role of climate change in

causing losses in question. If it were the case that attribution statements based on these two metrics are representations of the effect of climate change on impacts and of equal legal relevance, this could introduce an obstacle to establishing causation in court.

As climate change attribution studies have been extended from considering the role of human influence in physical hazards to also including their social, physiological and economic impacts, recent literature has questioned the applicability of probability-based assessments of human influence as they concern a 'class of events', rather than the specific impact experienced by claimants.[83] In other words, assessments of changing probabilities quantify changes in the chance of *exceeding a threshold value*. This would correspond to the change in probability of the impacts suffered by a claimant only if there is a threshold value above which the claimants' losses occur. Probability-based assessments can therefore assess the effect of climate change in settings where the relationship between a physical hazard (such as rainfall intensity) and the resulting impacts (for instance, whether or not a river bursts its banks and floods the surrounding area) is binary, in that the impacts occur only beyond a certain threshold.[83]

By contrast, continuous hazard-impact relationships, such as the impact of temperature on mortality,[84] is more accurately described by intensity-based framings of attribution findings: other than at the temperature of minimum mortality, it is generally not the case that were temperatures below a threshold value none of the observed heat-related deaths would have occurred (section 6). The intensity-based approach to conducting attribution analyses can also circumvent concerns raised by Perkins-Kirkpatrick et al.[83] as, rather than evaluating human influence on a class of events, it assesses the changed intensity of events of a specific probability. The choice of attribution metric is discussed in more detail in section 6.

Different attribution metrics can provide apparently contrasting assessments of the role of climate change in an impact. However, the specific question asked by these framings of attribution results differs: the metric (intensity or probability-based) used should be tailored to the setting in which it is being applied. To date, most existing literature[17,18,22,26] on the use of attribution-science evidence to support causal claims has focused on legal approaches to

applying attribution evidence of changing event probabilities. For instance, in England & Wales, the 'doubling-of-the-risk test' allows courts to establish causation when evidence demonstrates that the likelihood of an event occurring was at least twice as high as a result of defendants' conduct. Future legal research could consider how causal analysis in law should be conducted in the context of attribution of changing event intensities.

3.2.4 Further characteristics of attribution science

In common with many forms of scientific inquiry, the findings of attribution studies depend on methodological choices made in the analysis. Such choices include the 'event definition' used for meteorological and impact attribution studies, which describes the temporal and spatial scale of the analysis, and the parameters that will be analysed (such as which meteorological variables are assessed).[46] Attribution studies can provide sensitivity analyses that quantify the extent to which the findings depend on these choices. Nevertheless, ensuring the event definition is selected to quantify the effect of climate change on legally-relevant impacts is essential but remains a challenge for conducting some impact-relevant attribution studies.

Another charge occasionally levelled at attribution science is that the findings of these studies are uncertain due to limitations in models' abilities to accurately simulate the climate system and limited climatic observations to evaluate how well models perform in representing the climate. These challenges are by no means unique to attribution studies, but apply to studying the climate system in general, are widely documented, and similar considerations exist for most fields of scientific inquiry. Systematic approaches for quantifying the magnitude of uncertainties are deployed in attribution studies[85] and the sensitivity of results to these uncertainties can therefore be quantified. Moreover, improvements in modelling approaches, including the use of high-resolution models for attribution analyses,[47] may continue to reduce uncertainties in attributing a range of impacts to climate change.

3.3 Attribution science in litigation seeking emission reductions

Domestic climate policies worldwide remain insufficient to meet the goals of the Paris Agreement. Recent strengthening of climate pledges, if implemented in full (including targets that are conditional on the receipt of finance for emission-reduction measures) may be sufficient to limit global warming to 2 °C above pre-industrial levels.[86] However, the policies that have been introduced still lag the ambition of climate pledges that themselves are insufficient to meet the Paris Agreement's target of limiting warming to 1.5 °C. The United Nations Environment Programme's 2022 Emissions Gap Report found that under existing policies, global temperature rise is expected to reach 2.8 °C above pre-industrial levels by 2100. Even if all NDCs were implemented, including those conditional on the receipt of financial support from other states, warming would only be limited to 2.4 °C.[87] The International Energy Agency has stated that there is already enough installed fossil fuel infrastructure raise global temperatures to 1.5 °C above pre-industrial levels if installed infrastructure is used for its expected lifespan.[88] Even with widespread deployment of carbon capture and storage (CCS) and bioenergy for emissions abatement, already-operating, under construction and planned power plants will produce more emissions than are compatible with limiting warming to 2 °C.[89] In other words, new fossil fuel infrastructure is incompatible with the Paris Agreement, unless a commitment to decommission existing infrastructure is made.

In growing numbers of legal claims, claimants have argued that inadequate corporate or state emission reduction targets or policies, the approval of emitting infrastructure, or the permitting, financing, construction or operation of fossil fuel projects contravene a duty of care owed to claimants.[*] In such suits, the remedy requested is typically not financial compensation. Rather, claimants typically seek injunctions for strengthened emission reduction targets over a certain period, the withdrawal of planning permission for individual projects, or the cessation of public financing of fossil fuel infrastructure. While the nature of

[*] See, e.g., *Milieudefensie v. Royal Dutch Shell plc.*, *Sharma and others v. Minister for the Environment*.

claims and therefore the scientific evidence that may be introduced to support them varies, there are two core elements of legal arguments that may require scientific input. The first is to establish that claimants are impacted by defendants' actions and that a positive ruling would reduce the impacts experienced. Such arguments are typically advanced to meet requirements for standing,[15] or in support of claims that a state has a duty of care to minimise or prevent climate change impacts.[90] The second is for claimants to show that the emitting activities of defendants, be it their entire climate policy or the approval of individual projects, are inconsistent with certain duties, such as those associated with the Paris Agreement or domestic legislation. Here, I discuss how attribution science evidence may be advanced in support of the first of these arguments.

3.3.1 How claimants are seeking mitigation action through the courts

'Systemic mitigation' cases describe those that seek to change government or corporate climate targets or policy and have included challenges to states' 2030 nationally determined contribution (NDC) to the Paris Agreement, domestic emission reduction targets prior to 2030, post-2030 targets, and carbon budgets allocations for specific periods.[90] These cases have been brought as rights-based, tort-based, and public law claims. Such claims challenge the absence of greenhouse gas emission reduction commitments in a given period, a state's failure to meet its own carbon budgets or emission-reduction targets, inconsistency between targets (for instance those covering different periods of time), or the weakening of a state's emission-reduction target in contravention of the 'ratchet' mechanism introduced under Article 4 of the Paris Agreement.[*;12] Further cases have challenged inappropriate temporal distribution of mitigation effort, typically in the form of inadequate short-term targets that leave an excessively large portion of emission reductions to latter decades, excessive reliance

[*] Article 4 of the Paris Agreement states that 'Each Party's successive nationally determined contribution will represent a progression beyond the Party's then current nationally determined contribution and reflect its highest possible ambition'.

on negative emissions technology,[*] and targets that fall short of a state's fair-share contribution to emission reductions under the Paris Agreement.[90]

Cases challenging individual projects on the grounds of their contribution to climate change have also been brought worldwide and are one of the most commonly employed legal strategies to address climate change. These cases have been brought on the grounds of constitutional, human rights, and administrative law, as well as invoking international obligations.[91] Such cases have included challenges to national or sub-national governments for either failing to reduce emissions sufficiently or for causing an increase in emissions. Litigation of this type has concerned planning permission for projects such as coal mines, power plants or airport expansion,[†] and public financing of fossil fuel infrastructure.[‡] Other cases have been brought against corporations to block the construction of fossil fuel infrastructure,[§] or by corporations challenging the denial of permission for high-emitting projects.[**]

3.3.2 Scientific evidence for climate mitigation litigation

Mitigation-focused litigation often seeks to advance claims that a defendant should act to limit the exposure of some (likely to be) affected party to the consequences of climate change, although the precise legal grounds for such claims may vary substantially. Legal arguments made to this end include claims that contributions to climate change violate, or risk violating,

[*] The reliance on negative emissions technology in climate targets may allow emitting assets to be built that would otherwise be adjudged incompatible with climate targets. However, negative-emissions technologies may be subject to substantial risks, including relating to the permanence of carbon stores, (lack of) institutional guarantees for the deployment of carbon removal, and social and environmental harm associated with its use, including substantial requirements for land use. See, e.g. ref. [252]

[†] E.g., *Plan B Earth v Secretary of State for Transport*; *Bennett v. Cumbria County Council*; *Save Lamu v. NEMA*.

[‡] E.g., *Friends of the Earth v. UK Export Finance*; *Kang et al. v. KSURE and KEXIM.*

[§] E.g., *Client Earth v. PGE*.

[**] E.g., *Gloucester Resources Limited v. Minister for Planning*.

duties of care.[*] Duty of care is a tort law concept that describes the standard of reasonable care for legal entities in their treatment of third parties, particularly while performing acts that could foreseeably harm others. Similarly, to establish standing, claimants may need to demonstrate that the conduct of defendants (i.e., greenhouse gas emissions) has led to impacts that claimants are experiencing or are projected to experience. In these instances, climate change attribution and projections can support the assessment of past or future (conditional on scenarios of future greenhouse gas emissions) impacts of climate change. For instance, in the Application to the European Court of Human Rights in KlimaSeniorinnen v Switzerland, claimants sought to establish their victim status by arguing that they are already affected by 'dangerous climate change' in the form of mortality and morbidity associated with more extreme heat. Claimants argued that the risks of extreme heat to which they are exposed had been worsened by climate change, including due to the Swiss government's failure to make adequate emission reductions.[†] These arguments could be supported with attribution-science evidence demonstrating the impact of climate change on heat-related mortality and morbidity in the region where the claimants live. In section 6, such a study is conducted for the Canton of Zürich, Switzerland. The methodological innovations described in that paper may also support others of the growing number of cases brought on human-rights grounds, for which insight into the impacts of climate change on health is especially pertinent.

It should be noted that other forms of climate change impact science can play an important role in such claims, notably projections of future impacts. In a lawsuit filed in 2021, Pabai Pabai and Paul Kabai, seek to protect their communities in the Torres Strait islands from harms associated with climate change, including sea-level rise and coastal erosion, ocean acidification, intensifying and more frequent extreme weather events, and harm to ecosystems and human health. In the case, pending in the Federal Court of Australia at the

[*] See, e.g., *Milieudefensie et al. v. Royal Dutch Shell*.

[†] App no 53600/20 Verein Klimaseniorinnen Schweiz v Switzerland (ECtHR, pending).

time of writing, the claimants used projections of future sea-level rise and other climate change impacts to demonstrate that the Australian government has failed to take steps to fulfil its duty of care to the Torres Strait islands communities, and therefore that the Australian government should increase its mitigation efforts and support for adaptation action.[*]

In recent rulings, courts have used climate-science evidence to find that even small contributions to climate change can be causally linked to impacts, thus providing claimants with standing to sue, or establishing a duty of care for defendants. In *Milieudefensie et al. v. Royal Dutch Shell*, the District Court of The Hague ordered Shell to reduce its operational emissions by 45% by 2030 (compared with 2019 levels) and found that Shell has a 'significant best-efforts obligation' to reduce CO_2 emissions produced by the products (including oil and gas) of its subsidiaries worldwide by the same amount. In reaching this ground-breaking judgement, the court concluded that 'every emission of CO_2 and other greenhouse gases, anywhere in the world and caused in whatever manner, contributes to' 'environmental damage and imminent environmental damage' suffered by claimants in the Netherlands.[†] The scientific bases for climate change attribution and projections is closely related, including in the models used. The recognition by courts that scientific evidence of this type can be used to demonstrate defendants' contributions to specific impacts may also indicate the potential of claims based on attribution-science evidence.

Similarly, in *Gloucester Resources v. Minister for Planning*, Justice Preston at the New South Wales Land and Environment Court held that 'there is a causal link between the … cumulative GHG emissions [of an individual coal mine] and climate change and its consequences… In this way, the Project is likely to have indirect impacts on the environment,

[*] *Pabai Pabai & Anor v. Commonwealth of Australia*, statement of claim available at: https://fedcourt.gov.au/__data/assets/pdf_file/0003/96609/2021.10.26-Statement-of-Claim.pdf Accessed 21.08.2022.

[†] *Milieudefensie v Royal Dutch Shell* [2021] District Court of the Hague ECLR:NL:RBDHA:2021:5339 (official translation), p. 25.

including the climate system, the oceanic and terrestrial environment, and people'.[*] Similar reasoning was offered by President Kingham at the Land Court of Queensland, Australia, in a judgement handed down in November 2022, in the case of *Waratah Coal Pty Ltd v Youth Verdict Ltd & Ors*. In this case, a 'sufficient causal relationship' was found between the proposed approval of a coal mine and harms associated with climate change impacts resulting from greenhouse gas emissions associated with the mine. On the grounds of the climate change and local ecological impacts associated with the prospective mine, the project was considered not to be in the public interest and rejected accordingly.[†]

Cases seeking compensation for climate-related impacts have not yet advanced to a point where causation has been established. *Lliuya v. RWE* is the furthest advanced such case, with the court having initiated an evidentiary phase that is ongoing at the time of writing. Nevertheless, courts have begun to accept that even relatively small contributions to emissions can constitute breaches of duties of care. While such findings may be subject to more relaxed standards of proof than causal claims in suits seeking financial compensation for the impacts of emissions, it may bode well for future compensation claims too.

3.4 An agenda for research

Section 3.1 of this thesis set out a brief overview of recent developments in climate change attribution science. This thesis conducts attribution analyses that span glaciology, attribution of regional climate trends, and epidemiology. Further details about the specific methods used in these fields are provided in sections 5 and 6 (papers 2 and 3). In section 3.2, I assessed the implications of attribution-science developments for climate-related legal action. There, the thesis argues that methods in climate change attribution science could be applied to establish causal relationships between the greenhouse gas emissions of defendants in climate lawsuits, and impacts suffered by plaintiffs. Section 3.3 explains how climate change impact science

[*] *Gloucester Resources Limited v. Minister for Planning* [2019] NSWLEC 7.

[†] *Waratah Coal Pty Ltd v Youth Verdict Ltd & Ors* (No 6) [2022] QLC 21.

has been leveraged in support of claims seeking emission reductions, with outcomes favourable to climate change mitigation in some cases.

The potential for climate change attribution science to support legal claims thus demonstrated, the ensuing chapters of this thesis build on this analysis. First, the use of attribution-science evidence in past climate-related lawsuits is evaluated, including judicial interpretation of causal claims made by claimants. Second, an attribution case study is presented for the glacial lake outburst flood hazard from Laguna Palcacocha (Peru) to explore how state-of-the-art attribution methods can strengthen causal claims brought in climate lawsuits. Third, paper 3 addresses the growing focus on rights-based claims in climate litigation and proposes advances in methods for attributing health impacts to climate change. While the case study provided in paper 3 may be of relevance for *KlimaSeniorinnen v Switzerland* (pending at the time of writing at the European Court of Human Rights), the methods described could be applied more widely to provide insight on the growing burden of health, economic, and social impacts of climate change being experienced worldwide, and which are subject to growing legal scrutiny.

4 Filling the evidentiary gap in climate litigation

Paper 1 analyses the scientific evidence introduced to support arguments of causal relationships between greenhouse gas emissions and climate change impacts in existing climate-related lawsuits, how this evidence compares to the state-of-the-art in climate science, and how this evidence has been interpreted by courts. We analysed the scientific evidence used in 73 legal cases from 14 jurisdictions that either referred directly to attribution science or used evidence to claim that climate change is or will become responsible for particular damages. We then considered the judicial interpretation of this evidence, where judgements were available.

The findings of this research project were initially published as a research article in *Nature Climate Change*[21] and as a practitioner-focused report in English[*] and Spanish[†] in June 2021.

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[*] Available at: https://www.smithschool.ox.ac.uk/sites/default/files/2022-03/attribution-science-and-litigation.pdf

[†] Available at: https://www.smithschool.ox.ac.uk/sites/default/files/2022-07/La-ciencia-de-la-atribucion-y-litigios.pdf

Filling the evidentiary gap in climate litigation

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Lawsuits concerning the impacts of climate change make causal claims about the effect of defendants' greenhouse gas (GHG) emissions on plaintiffs and have proliferated around the world. Plaintiffs have sought, *inter alia*, compensation for climate-related losses and to compel governments to reduce their GHG emissions. To date, most of these claims have been unsuccessful. Here, we assess the scientific and legal bases for establishing causation and evaluate judicial treatment of scientific evidence in 73 lawsuits. We find that the evidence submitted and referenced in these cases lags considerably behind the state-of-the-art in climate science, impeding causation claims. We conclude that greater appreciation and exploitation of existing methodologies in attribution science could address obstacles to causation and improve the prospects of litigation as a route to compensation for losses, regulatory action, and emission reductions by defendants seeking to limit legal liability.

Plaintiffs have brought over 1,500 climate-related lawsuits worldwide, and the number of claims filed continues to increase[92]. Without effective non-judicial mechanisms providing compensation for climate-related loss and damage, plaintiffs have filed lawsuits seeking financial remedies from high-emitting corporations for losses suffered due to climate change[93]. Robust scientific evidence is critical to the success of such claims[18,22,94]. For example, claims for compensatory damages must demonstrate a causal link between the defendant's behaviour and the plaintiff's injury. Recognising this, recent literature has drawn on analogous categories of case, such as toxic torts, in which modified causation tests

reconcile legal causal analysis with scientific evidence that demonstrates multiple entities' contribution to the risk of harm[22]. However, despite developments in scientific[95] and legal theory[22] on causation and attribution of climate change damages, compensatory-damages claims have been unsuccessful. Other lawsuits challenge inadequate state and corporate climate change mitigation targets and policies[23]. To establish admissibility, these claims may also rely on courts finding that emissions resulting from defendants' policies led to impacts affecting the plaintiffs.

A claim must first meet procedural requirements that render it admissible, including 'standing', which establishes that plaintiffs have legally protected interests that entitle them to bring the claim. Demonstrating a connection between defendants' actions and plaintiffs' injuries may contribute to meeting the standing requirement. To date, admissibility has been the primary outcome-determinative obstacle for climate litigation[15]. If claims pass procedural hurdles, more stringent causation standards for attributing losses to defendants' actions are applied to determine plaintiffs' entitlement to relief (remedies).

To establish causation, the court needs to receive scientific evidence, including through expert witness testimony, bounded by rules on the expert's independence and duties to the court, and amicus briefs submitted by third parties. Courts interpret this evidence through the lens of legal reasoning[22]. Such legal rules, encompassing both "normative correctives" applied to evidence[22] and the standard of proof, vary between jurisdictions (Supplementary Information, 'Standards of proof in law'). Across jurisdictions, however, courts ascribe value to authoritative sources of evidence such as Intergovernmental Panel on Climate Change reports or peer-reviewed publications[96]. The *a priori* question motivating this research is whether the scientific evidence courts were provided with and have access to reflects the 'state of the art'.

Challenges to scientifically demonstrating causation

The fields of event attribution and trend detection and attribution evaluate the causal relationships at issue in climate litigation. Attribution science comprises methods which

generally use counterfactual inquiry to link observed trends or changes in probability or intensity of climate-related events to human influence. Existing methods can quantify the contribution of GHG emissions to specific events, including (1) extreme events, including storms[97], droughts[98], heatwaves[45], or floods[99], (2) long-term trends in glacier lengths[3] or sea levels, and (3) persistent changes, for instance in mean temperatures or precipitation[37]. Despite the clear relevance of attribution-science evidence, there is limited precedent for courts to base findings of causation on such evidence, partly due to its relative novelty. In common with most forms of scientific evidence, including regarding the health consequences of exposure to pharmaceutical substances, courts' use of climate-change attribution evidence to assess causation is subject to several considerations.

First, GHG emissions are fungible and climate-change impacts result from the cumulative emissions of multiple parties. This underlies use of 'market share theory'[22], an approach which, following precedent in pharmaceutical and tobacco litigation, allocates damages among defendants according to the portion of emissions for which they are responsible[18]. Market share theory has been used to allocate damages in cases where losses derive linearly or non-linearly from multiple entities' actions, to reduce evidentiary challenges in calculating defendants' exact contributions to losses. It is recognised that this simplistic allocation basis may not exactly reflect defendants' contributions to losses. Attribution-science evidence quantifying individual defendants' contributions to plaintiffs' losses directly could be used instead of the market-share approach. This may be helpful for impacts with non-linear emissions-impact relationships[100].

Second, extreme weather events generally occur due to the combination of human influence and the underlying chance that they would occur naturally. Climate lawsuits aim to follow past science-based tort litigation such as product liability cases, which sought compensation for medical conditions arising from exposure to pharmaceutical substances, tobacco smoke and asbestos[18]. Such conditions may have occurred in the absence of this exposure. Similarly, climate change may increase the likelihood or intensity of an extreme event so attribution statements are typically probabilistic. Legal frameworks exist for holding defendants

responsible for changes in an event's probability even if they make only a partial contribution to this change[18,22]. Standards of legal proof for probabilistic evidence may differ from the likelihoods evaluated in scientific assessments[18] (Supplementary Information, 'Standards of proof in law').

Finally, in common with many types of expert evidence, attribution findings are question-dependant[57] and influenced by the event definition. Contrasting approaches to framing attribution questions produce quantitatively differing results, while remaining scientifically valid[101]. These approaches vary in their alignment with the logic of legal causation (Supplementary Information, 'Approaches to conducting attribution studies'). Further, attribution assessments apply statistical methods to assess confidence and uncertainty in results[102]. Sources of uncertainty include limitations in model representations of the climate system and climatic observations for model evaluation. Uncertainty is assessed based on physical understanding of atmospheric processes and their representation in models, agreement between models and observations, and the quality of available evidence[57].

Climate science evidence in past litigation

How well does the evidence submitted to climate-related lawsuits compare to the state-of-the-art in climate science? A growing body of literature explores the role attribution science can play in climate-related litigation, from legal and scientific perspectives[17,18,20,22]. This is the first global study of the use and interpretation of climate-science evidence in lawsuits. We identify the scientific evidence needed to make successful causal arguments and analyse the evidence provided by plaintiffs and defendants in 73 cases across 14 jurisdictions (Methods, Table 1, listed in full in Supplementary Table 1).

We consider cases that advance claims that defendants' GHG emissions impacted plaintiffs (Methods). Our analysis finds that most cases did not quantify the extent to which alleged impacts are attributable to climate change and fewer still provided quantitative evidence linking defendants' emissions and plaintiffs' injuries. Although some recently-filed cases provided stronger evidence, e.g., refs. [103–105], 73% of cases did not refer to peer-reviewed

attribution studies. Most of the cases that referred to attribution findings did so to establish general links between emissions and certain types of climate-change impacts, rather than to attribute losses sustained by plaintiffs. Moreover, despite substantial evidence that climate change increases the probability and intensity of a range of events, not all climate-related hazards are affected by climate change[57]. This underlines the importance of providing evidence specific to the impact for which a causal link is alleged[18,22].

54 cases cited meteorological extremes as the cause of alleged impacts (Supplementary Table 2). Of these cases, 26 claimed that weather events occurred due to climate change, without providing evidence. A further 6 provided no quantitative estimate of the influence of climate change on the event's magnitude or probability. Losses stemming from extreme weather events cannot be presumed attributable to climate change *a priori*[106]. Even for events where climate change plays a substantial role, GHG emissions will increase the event's likelihood or intensity, rather than being its sole cause[107]. Further, many legal claims concerned events, such as tropical cyclones, for which evidence of human influence is limited[108], or for which technical obstacles to conducting attribution assessments exist[97]. However, climate change substantially influences other events with considerable humanitarian consequences, such as heatwaves and some droughts[109]. Establishing causation is easiest for events where the influence of climate change is greatest: these are logical subjects of climate lawsuits.

38 cases made causal allegations related to sea-level-rise impacts. Human influence is very likely the dominant cause of global-mean sea-level change since 1970[110]. However, regional sea levels may differ due to natural and human-influenced processes, modifying the anthropogenic contribution to impacts. These processes include regional variation in thermal expansion and ocean and atmospheric circulation, glacial-isostatic adjustment, and land subsidence[110]. Factors such as subsidence outweigh the effect of human-induced climate change in some regions[111]. 12 cases concern impacts of glacier retreat (Supplementary Table 2), an established consequence of climate change[3]. However, individual glaciers' response to climate change depends on their geographic and climatic settings[112]. Linking emissions to glacial and sea-level-rise impacts at the appropriate level of specificity for establishing legal

causation may require evidence on these local factors (Box 1). This is uncommon in the cases analysed.

The evidence needed for legal causation

Many of the lawsuits assessed here are at the early stages of adjudication or were dismissed before substantive consideration of causation arguments. Our analysis of courts' interpretation of scientific evidence considers all lawsuits in which courts evaluate this evidence, including cases that were ultimately dismissed for reasons unrelated to issues of causation.

Courts evaluate scientific evidence by applying tests that set evidentiary thresholds for establishing causation. Across jurisdictions, causal analyses focus on the relationship between defendants' conduct and plaintiffs' losses, but the tests and standards of proof applied vary (Supplementary Information, 'Causation tests used in climate litigation'). In some cases, claimants have had to show that the defendant's actions constituted material contributions to harm[113,114]; others applied causality tests more flexibly. However, plaintiffs have been unable to overcome even the more flexible causation tests applied in several jurisdictions which ask if damages are 'fairly traceable' to defendants' actions[115–117]. This is typically due to courts' finding that the evidence provided does not substantiate the connection between individual emitters' actions and plaintiffs' losses. In our view, in most cases concerning impacts for which the causal link to climate change does exist, existing scientific methodologies could fill the evidentiary gaps identified by courts.

Our analysis shows that when courts considered evidence on causation, they typically found that plaintiffs failed to demonstrate that defendants' emissions caused the alleged impacts. Plaintiffs have claimed, with or without supporting evidence, that climate change caused certain harms and therefore that defendants' GHG emissions render them liable for a portion of these losses. In claims seeking compensation for climate-change impacts brought in the US, Germany and New Zealand, courts found that plaintiffs failed to demonstrate that their injuries would not have occurred in the absence of defendants' emissions. These findings

were due to defendants' small contribution to climate change[118], the high number of emitters responsible[114], the absence of a method for discerning entities responsible for impacts[119], and the lack of a direct causal link between defendants' actions and losses[113,115,116,120–122]. In some cases, courts have incorrectly stated the infeasibility of attributing climate impacts to individual emitters[114]. Similarly, in claims seeking emission reductions, courts found that plaintiffs failed to demonstrate how a positive judgement would reduce climate-change impacts[114].

In our view, these findings are not a product of technical limitations preventing the production of required evidence. Scientific evidence on the influence of individual actors' GHG emissions is available for existing[30,32,81] and projected impacts[31].

Despite inter-jurisdictional variation in the standards of proof for causation, there are shared characteristics of evidence needed to support claims. Cases seeking compensation for adaptation costs must demonstrate that (1) risk mitigation measures are required, and (2) the cost sought is a consequence of climate change resulting, in part, from defendants' actions. Evidence submitted in cases of this type generally demonstrated that the hazards threatening plaintiffs' property and wellbeing were substantial and required hazard-mitigation measures. However, the evidence for causation was typically much weaker, despite availability of the scientific methodologies needed to generate it (see above). Cases claiming that adaptation policies are inadequate may argue that losses were foreseeable due to climate change (e.g., ref. [123]) which may in turn be supported by attribution-science evidence.

Lawsuits seeking emission reductions considered in this analysis (Methods) make causal claims about the impact of a positive judgment on projected impacts, usually to establish legal standing. Our analysis shows that a case was dismissed by a court in the U.S.[124] partly due to plaintiffs' failure to establish standing because they did not demonstrate that emission reductions would reduce the impacts they experience. Scientific evidence linking defendants' GHG emissions to future impacts would address this finding.

The evidence gap in climate litigation

The existing literature suggests that there are real challenges to satisfying causation tests in climate-related litigation[18,22]. In our view, at least some of these challenges can be addressed by better exploiting scientific developments, particularly in the field of climate-change attribution. It is therefore crucial that plaintiffs have access to this science, and that this evidence is brought to the attention of courts. Our analysis identifies three areas where scientific research could address existing evidentiary shortfalls: (1) attribution of climate-change impacts to individual emitters of GHGs[30–32,81] (possible using existing attribution-science methods), (2) research on the foreseeability of climate-change impacts resulting from future emissions, and (3) research disentangling the legally-relevant social and physical drivers of climate risks and impacts. The latter recommendation is the most methodologically challenging, due to challenges in quantifying non-climatic contributions to impacts.

Establishing a defendant's contribution to plaintiffs' losses has presented a key challenge in cases in which causal claims have been adjudicated. However, current scientific methodologies enable quantifying individual emitters' marginal contributions to extreme weather events and slow-onset changes[30,32,81]. Methods for modelling the response of the climate system to excluding certain GHG emissions exist[80] and have been applied to evaluate the contribution of countries' emissions to extreme-weather probabilities[81]. Evidence of this type appears capable of plugging evidentiary gaps identified in some prior cases[113,115,116,118–122]. In some lawsuits seeking emission reductions, plaintiffs argued that implementing emission-reduction measures would reduce otherwise anticipated impacts, typically to establish standing. In one case, the court found that defendants had not breached legal duties as plaintiffs failed to demonstrate how requested emission reductions would affect the magnitude of climate-change impacts[124]. Counterfactual analyses could support these claims by assessing individual emitters' contributions to projected changes in impacts under future climate change (e.g., ref. [31]).

Our analysis also suggests that there is scope to develop evidence which provides a more complete assessment of the drivers of losses on which claims are based. Climate-related losses result from physical events, about which attribution science provides evidence, mediated by

communities' exposure and vulnerability to these hazards[125]. Research that evaluates the relative importance of different drivers and which of these factors constitute the legally relevant cause(s) of losses may support establishing defendants' liability for climate impacts.

Finally, although most attribution findings are presented in terms of changing event probability, 48% of cases analysed made claims about the impact of climate change on the magnitude, rather than probability, of events. Attribution evidence on event intensities can be provided using existing methods (e.g., refs. [45,97]) and may be more informative for some impacts, like adverse effects on human health[126]. Such evidence may also strengthen legal claims by providing an evidentiary basis for asserting that a defendant's conduct has made a plaintiff worse off. Attributing changes in event intensity to a defendant aligns with the logic of the 'but-for' test in law and may satisfy causation tests by showing how the magnitude of a harm was altered by an individual defendant's conduct. Future research could determine whether probability or intensity-based attribution metrics best assess the contribution of climate change to different types of losses.

Individuals, communities and activist non-governmental organisations have increasingly turned to the courts for relief for costs associated with present-day climate change impacts, or to avoid future impacts. While the cases we examined may not have been dismissed solely on evidentiary grounds, existing case law provides insight into the challenges that need to be addressed if future climate-related lawsuits are to succeed. As plaintiffs overcome initial procedural hurdles, such as standing, evidence on causation will become more determinative of case outcomes. Attribution science is a fundamental source of evidence for informing and substantiating causal claims about climate-change impacts, hitherto underutilised in law[17].

Our analysis of 73 cases from 14 jurisdictions finds that, in contrast to previous interpretations[15], limitations in the scientific evidence provided to past lawsuits may have hindered the making of findings of causation. This conclusion is based on the finding that such evidence lags significantly behind the state-of-the-art in climate science. To maximise the chances of establishing causation in the courts, plaintiffs should ensure that (1) cases filed concern impacts that are demonstrably attributable to climate change, and (2) that evidence

submitted to the courts clearly substantiates the alleged relationship between defendants' emissions and plaintiffs' losses.

Across jurisdictions, courts have found insufficient links between defendants' emissions and plaintiffs' injuries. In some cases, courts have explicitly, and incorrectly, stated the infeasibility of scientifically attributing climate impacts to individual emitters[114,115]. This underlines the importance of dialogue between the legal and scientific communities on the factual basis for causal claims. Better dialogue would ensure that lawyers are aware of, and able to request, evidence that can be used to robustly evaluate causal claims. This could be achieved through selection of independent experts with relevant scientific expertise, such as Intergovernmental Panel on Climate Change authors, as well as (outside the context of any particular case) funding to support the continuing development of the science in this field. Effective use of climate-science evidence in the courts could overcome existing obstacles to causality, set precedent for demonstrating legal causality with climate-science evidence, and make successful litigation on climate-change impacts feasible.

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Author contributions

All authors planned the analyses which R.S.-S., A.S., and G.L. performed. All authors contributed to the interpretation of the results and to writing the manuscript.

Competing interests

The authors declare no competing financial or non-financial interests.

Box 1: Scientific evidence in past lawsuits

Case study 1: Lliuya v. RWE AG

In 2015, Saúl Luciano Lliuya filed a case against a German energy company, RWE, seeking compensation for the pro rata cost of measures taken to protect his property against climate change impacts, based on Article 1004 of the German Civil Code. This article applies the 'conditio sine qua non' test for causality: the plaintiff's injury would not have occurred fully or partially if not for the defendant's activity. The District Court of Essen dismissed the case, reasoning that RWE would not qualify as "disturber by conduct" under Section 1004 of the German Civil Code given that the number of contributors to climate change render attributing individual damages to specific actors impossible. On appeal, the Higher Regional Court of Hamm accepted that the case has been conclusively argued and initiated an evidentiary phase. The first stage of the evidentiary phase assesses whether the claimant's property is indeed seriously threatened by a potential glacial lake outburst flood, including a court visit to Peru. Subsequently, the court will assess evidence around whether the heightened flood risk is attributable to RWE, and finally whether the damage contributed by the defendant is measurable and can be calculated.

Recent research has demonstrated that it is indeed possible to provide an attribution assessment spanning the full causal chain in this setting[3].

Case study 2: Native Village of Kivalina v. ExxonMobil Corp.

In 2008, the Alaskan village of Kivalina filed a public nuisance claim seeking to hold 24 energy companies liable for coastal erosion, alleged to be due to climate change, which threatened the village, requiring it to be relocated inland. The Court applied the 'fair traceability' test, which requires the plaintiff to demonstrate a substantial likelihood that the defendant's conduct (emissions) was the seed of the plaintiff's injury. The U.S. Court of Appeals for the Ninth Circuit dismissed the lawsuit, in part due to the plaintiff's failure to establish standing through demonstrating causation. The Court ruled that the causal link between the defendant's activities and the plaintiff's damage was too indirect since "it is not plausible to state which emissions – emitted by whom … and at what place in the world – 'caused' Plaintiffs' alleged global-warming related injuries [because there are] a multitude of 'alternative culprit[s]' allegedly responsible for the various chain [sic] of events allegedly leading to the erosion of Kivalina"[115].

While attribution-science research specifically addressing the causal link alleged in this case (i.e., specific to the impacts at this location) does not yet exist, it would be scientifically possible to conduct a study to determine the extent to which defendants' emissions led to the losses experienced by Kivalina.

Table 1

Country	Number of cases	Successful	Dismissed	Pending
Australia	3	0	1	2
Belgium	1	0	0	1
Canada	3	0	0	3
Colombia	1	1	0	0
Germany	2	0	1	1
Ireland	1	1	0	0
Netherlands	2	1	0	1
New Zealand	4	1	2	1
Pakistan	2	1	0	1
Philippines	1	0	0	1
South Korea	1	0	0	1
Switzerland	1	0	1	0
Uganda	1	0	0	1
USA	45	3	21	21
International jurisdictions	5	0	2	3

Table 1: Number of cases and case outcome (as of November 2020) for lawsuits considered in this analysis, categorised by jurisdiction. Cases are listed in full in Supplementary Table 1.

Methods

Scope of case-law analysis

Our case law analysis covers cases that make claims about the past, present and future impacts of climate change and the relationship between GHG emissions and these impacts. We sought to analyse all lawsuits, brought using a variety of legal bases, where courts considered scientific evidence on causation. Cases were selected through a systematic review of the Sabin Center for Climate Change Law at Columbia Law School's climate litigation database (http://climatecasechart.com/) conducted in May 2020. The database categorises cases according to criteria such as the case objective (for instance, 'actions seeking adaptation measures') or the principal laws under which the claim was brought. Cases within relevant 'case categories' were identified and assessed for alignment with the project scope, including by searching for the presence of keywords pertaining to climate-change impacts in complaints. Claims in the following categories of the Sabin Center database were assessed for their relevance to the project scope: Adaptation (including 'Actions seeking money damages for losses'), Public Trust Claims, Common Law Claims, Climate Change Protestors

and Scientists, and claims brought under the National Environmental Policy Act (U.S.); Suits against Corporations, Public Trust, Human Rights, GHG Emissions Reduction and Trading, Climate Adaptation (non-U.S.). The review of the Sabin Center database was supplemented by a review of cases cited in relevant academic literature, e.g., refs. [15,18,127]. A review of news articles was used to identify cases filed during the period over which we conducted the analysis, in September 2020.

We identified a list of 73 cases from 14 national jurisdictions which either refer directly to attribution science or use evidence to claim that climate change is or will become responsible for particular damages. The cases determined to be within the project scope do not include those that refer only to general impacts of climate change. Rather, we only consider cases that make causal claims about impacts in specific locations, for which attribution-science evidence is relevant.

Cases identified within this scope fell into the categories of tort, human rights, public trust, takings, contract, judicial review, and federal statutory claims. The tort and human rights claims typically sought remedies in the form of financial compensation for climate change impacts or emission reductions. All 'damage liability' suits that were filed relied on causal argumentation about the relationship between emissions and impacts. By contrast, only a subset of pro-regulatory claims for emission reductions – typically brought as human rights claims, or, for U.S. cases, under the public trust doctrine – have sought to link the actions of defendants to specific climate-related losses. Those that did were included within the project scope (Supplementary Table 1). Similar lawsuits that did not make claims that defendant emissions caused specific climate-related losses were excluded from the analysis as attribution science evidence was not relevant to the legal arguments made in these cases. We note that, in future, attribution-science evidence may be used by a wider range of lawsuits[17,18].

In our evaluation of the scientific evidence provided by parties to the case, we considered for inclusion publicly available case documents submitted by plaintiffs, defendants, and other parties. Such documents included complaints, petitions, responses, motions, and amicus briefs. A list of key documents which were used to inform our findings, for each case, is

included in Supplementary Table 1. We included cases in early stages of litigation (for instance, for which only the complaint was available) but excluded two cases believed to be within the scope of the research for which either no court documents were available (Petition of Torres Strait Islanders to the United Nations Human Rights Committee), or for which court documents, or high-quality translations of them, were only available in languages not spoken by the research team (*Federal Environmental Agency (IBAMA) v. Siderúrgica São Luiz Ltd. and Martins*). Documents in English, Spanish, and French were included. In a small number of cases, such as *Friends of the Irish Environment v. Ireland*, the Petition or complaint could not be made public and so only the legal analysis of the judgement and appeal was possible.

We then identified court documents which introduced evidence or claims regarding the potential causal relationship between greenhouse-gas emissions and climate change impacts. As far as possible this was approached systematically through the use of a series of relevant search terms. We reviewed non-searchable documents manually.

Regarding the judicial assessment of the scientific evidence provided to cases, we considered final decisions and opinions, as well as court documents released during the pre-trial stage, such as orders to grant or dismiss motions to remand, orders to accept amicus briefs, or questions directed to expert witnesses.

Scientific analysis

The scientific analysis seeks to understand the nature of the attribution-science evidence used in climate-related legal cases. We identify key components of the evidence in each case within the project scope, through a review of complaints, expert testimony, and defendants' responses. These factors include (i) the type of attribution evidence provided in the case, (ii) the strength of attribution evidence as presented in the case (and as compared with that available in the published literature), (iii) the methodologies used to quantify attributable damages, and (iv) the content of expert testimony.

For each lawsuit, we evaluated the type of evidence provided on causation according to the source of the evidence used for alleging the existence of a causal link between GHG emissions and impacts. Evidence from Intergovernmental Panel on Climate Change (IPCC) reports has commonly been submitted by plaintiffs to substantiate claims, including in unsuccessful cases. IPCC attribution assessments of climate change impacts are typically regional or global in scale, and therefore do not provide evidence specific to damages alleged in most cases. To understand how different forms of attribution knowledge affect legal interpretation, we differentiate between cases that extrapolate from regional / global attribution statements, those where attribution is presumed based on consistency of impacts with published and peer-reviewed climate projections, those for which attribution is presumed with no supporting evidence, and those that use an attribution study into the causes of the impacts sustained by plaintiffs, and whether or not it has been peer-reviewed.

Further to our assessment of cited attribution evidence, where relevant, our analysis considers the expert testimony admitted to cases. This includes considering which experts are called upon and whether they have published in the field of attribution science.

Our analysis of the strength of attribution evidence used in within-scope cases considers the magnitude of human influence on the climatic event relevant to the litigation, and the confidence in and uncertainty associated with these findings. We can therefore assess the extent to which the magnitude of human influence found affects the legal determination of causality, in the context of jurisdiction-specific standards, such as the 'doubling of the risk' test in England and Wales[18]. Further, we considered any evidence provided about plaintiffs' pre-existing (independent of climate change) vulnerability to climate impacts, including defendants' use of pre-existing vulnerabilities to counter plaintiffs' arguments that there is a causal link between GHG emissions, and the impacts experienced.

Finally, we consider how assessment of the attribution of physical impacts corresponds to the damages sought in the case. For each lawsuit, we identify whether plaintiffs sought to claim that the entire cost of the damages was attributable to anthropogenic GHG emissions, or whether damages were quantified according to attributable changes in event intensity or

probability. We also consider whether economic and/or non-economic losses are quantified, what relief was requested, and how a defendant's contribution to losses was quantified in determining the requested relief.

Our assessment of the scientific evidence provided in the cases analysed includes the collection of qualitative – such as whether the type of evidence provided on causation was a peer-reviewed attribution study or a regional attribution statement from an IPCC report – and quantitative – for instance on the magnitude of economic relief requested – data, supplemented by expert judgements.

Legal analysis

For each lawsuit within the scope of the analysis, for which courts' opinions, decisions, orders, or judgements were available (Supplementary Table 1), we evaluated how the courts have assessed and interpreted the scientific evidence on causation brought before them. The immediate obstacles to the success of litigation have largely been on admissibility and procedural grounds[15], with causation evidence generally not being outcome determinative. Our analysis, therefore, evaluates judicial opinion on causal arguments irrespective of the immediate reason for the case outcome and identifies how attribution science evidence can best support litigation if non-evidentiary, procedural obstacles are overcome. We identify trends across jurisdictions and time in how attribution science has been used by litigants and interpreted by courts to overcome procedural and evidentiary hurdles to successful litigation.

Our legal analysis considers courts' use of scientific evidence in establishing the admissibility of a case (as used under English law: whether a court has jurisdiction to adjudicate on a matter) or in satisfying procedural and substantial requirements of the law. For a case to be admissible, plaintiffs must have standing to bring the lawsuit, and defendants must have legal duties to plaintiffs which they may have breached. We consider whether a court finds that a sufficient link exists between the losses experienced by plaintiffs and climate change, as well as the link between defendants' emissions and these losses. We also assess the extent to which courts find that plaintiffs' losses were foreseeable to defendants, and the admissibility of

expert testimony. We further identify whether courts find defendants to be liable for losses. Our analysis focuses on the extent to which deficits in scientific evidence played a role in a courts' assessments of these issues. We also consider the approaches courts have taken in responding to scientific arguments concerning defendants' contributions to alleged impacts, including the apportioning of liability based on market share of emissions or on defendants' marginal contribution to impacts.

In cases in which courts have directly engaged with causation arguments, we identify the tests applied by the courts, how these have varied between jurisdictions and over time, and the differences between these tests. We then consider the implications of these causation tests for the courts' evaluation of scientific evidence and the standards of proof that plaintiffs need to meet to bring successful climate change lawsuits.

Finally, we provide an overall assessment of the role of science in case outcomes and an analysis of the required changes in scientific evidence that would improve the likelihood of establishing causation in future cases. We contextualise this analysis in the challenges faced when applying existing legal concepts to novel, global challenges for which they may not be well suited[128].

Data availability: Case documents were sourced primarily from the Sabin Center for Climate Change Law at Columbia Law School's Climate Change Litigation database (http://climatecasechart.com/). Where relevant case documents were unavailable on this database, they were sourced from individual courts' public databases or from Westlaw.

5 Increased outburst flood hazard from Lake Palcacocha due to human-induced glacier retreat

Paper 2 assesses of the role of anthropogenic climate change on the hazard of a glacial lake outburst flood from Laguna Palcacocha, a moraine-dammed pro-glacial lake in the Cordillera Blanca mountains, Perú. While paper 1 provides empirical support to the assessment of legal scholars that attribution science can play an essential role in supporting causal claims in climate lawsuits, paper 2 is the first dedicated attribution study conducted in the context of a climate lawsuit, and is a source of evidence in a pending lawsuit, *Lliuya v. RWE*.

Prior to the publication of this article, statements about the role of climate change on the outburst-flood hazard from Lake Palcacocha provided in the complaint were relatively equivocal about the role of climate change, and necessarily regional or global in scale. Statements included that 'glaciers worldwide are retreating *partly due to* increases in local temperature levels', 'to the extent to which this scientific statement is possible, the glaciers would *not have melted as rapidly* without the anthropogenic greenhouse effect', and that '*more than half* of observed' global-mean temperature rise over 1951-2010 could be attributed to anthropogenic influence on the climate.[*] In this analysis, we considered how developments in attribution science could facilitate a more specific assessment of the role of climate change in this setting.

The findings of this research were published in *Nature Geoscience* in February 2021,[3] with a Spanish translation made available soon after publication.[†]

[*] Rechtsanwälte Günther, lawsuit from 24 November 2015 (Saúl Ananías Luciano Lliuya ./. RWE AG, Landgericht Essen, Az.: 2 O 285/15). Redacted English translation available at https://www.germanwatch.org/sites/default/files/announcement/20822.pdf (Accessed: 29 November 2022).

[†] Available at: https://www.geog.ox.ac.uk/graduate/research/Stuart-Smith_et_al-NatGeo2021_Spanish.pdf

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Increased outburst flood hazard from Lake Palcacocha due to human-induced glacier retreat

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A potential glacial lake outburst flood from Lake Palcacocha (Cordillera Blanca, Peru) threatens Huaraz, a city of 120,000 people. In 1941, an outburst flood destroyed one-third of the city and caused at least 1800 fatalities. Since preindustrial times, Lake Palcacocha has expanded due to the retreat of Palcaraju glacier. Here we use observations and numerical models to evaluate the anthropogenic contribution to the glacier's retreat and glacial lake outburst flood hazard. We find that the magnitude of human-induced warming equals between 85 and 105% (5-95% confidence interval) of the observed 1 °C warming since 1880 in this region. We conclude that it is virtually certain (>99% probability) that the retreat of Palcaraju glacier to the present day cannot be explained by natural variability alone, and that the retreat by 1941 represented an early impact of anthropogenic greenhouse gas emissions. Our central estimate is that the overall retreat is entirely attributable to the observed temperature trend, and that the resulting change in the geometry of the lake and valley has substantially increased the outburst flood hazard.

The worldwide retreat of mountain glaciers is one of the most prominent impacts of climate change in public discourse and an established consequence of anthropogenic climate change[39,129,130], with Andean glaciers among the fastest retreating[130,131]. Mountain glacier lengths have decadal-to-multidecadal response times[51,132] and act as lowpass filters of climate[132,133]. They therefore represent a purer signal of anthropogenic climate change than most other metrics. However, any individual glacier's response to climate change depends on its geographic and climatic setting[39,129,134]. An assessment of the human contribution to an

individual glacier's retreat and hence changing glacial lake outburst flood (GLOF) hazard must quantify these factors and place the observed change in the context of the natural variability expected in the absence of anthropogenic climate change.

GLOFs are a dangerous hazard in deglaciating alpine environments, and downstream inundation from large outburst floods have caused serious damage to human settlements[135] and infrastructure[136]. GLOFs can occur from englacial, subglacial, supraglacial, and proglacial lakes. GLOFs from proglacial lakes that form in the wake of a retreating glacier, such as Lake Palcacocha, are a response to the disequilibrium imposed on glacial landscapes by climate change[6,137]. They occur when an unstable moraine dam is breached or a moraine-overtopping wave is induced by a triggering event, such as a landslide or an avalanche[138]. However, the anthropogenic influence on a specific GLOF has hitherto not been evaluated[135]. In the mid-20th Century, new proglacial lakes formed throughout the Cordillera Blanca as glacier termini receded[139] and multiple fatal GLOFs were recorded, including from Lakes Ayhuinyaraju, Jancururish, Tumarina, and Palcacocha[140]. Ongoing GLOF hazard continues to require extensive mitigation and engineering efforts[4,141]. We focus here on Lake Palcacocha which currently threatens the city of Huaraz with a GLOF[4,6,130,137,138,142,143].

Lake Palcacocha (9°23'49"S 77°22'47"W) sits at the foot of Palcaraju glacier. Lichenometric dating of Palcaraju glacier's terminal moraine indicates a 17th-Century formation, which sets the maximum extent of the glacier in the last few centuries[140,144]. Photographic records of Palcaraju glacier (Fig. 1) show the 1939 terminus set well back from the terminal moraine, with an over-spilling Lake Palcacocha between the glacier's terminus and terminal moraine. In 1941, the breaching of Lake Palcacocha's moraine dam resulted in the Cordillera Blanca's deadliest GLOF of the 20th Century[140]. The resulting debris flow destroyed one third of Huaraz and killed at least 1800 people[1,6,139]. Limited expansion of Lake Palcacocha was observed between 1948 and 1995, and lake area increased from 0.06 to 0.08 km^2. The rapid retreat of Palcaraju glacier since 1995 has expanded the lake to an area of 0.49 km^2 in 2018[5]. Two concrete overflow spillways were installed in the terminal moraine between 1972-1974. Until 2011, the lake-surface elevation had remained constant and lake volume grew as

Palcacocha expanded into space previously occupied by the retreating glacier. In 2011, siphons were installed to lower the water surface by 3-5 m, although GLOF hazard remains high[6]. The most recent bathymetric survey found the volume of Lake Palcacocha was 17,403,353 m^3 in 2016[145], a 34-fold increase from the volume of the post-GLOF lake in 1941, making it the 4th largest of the 35 glacial lakes with installed safety features in the Cordillera Blanca[4].

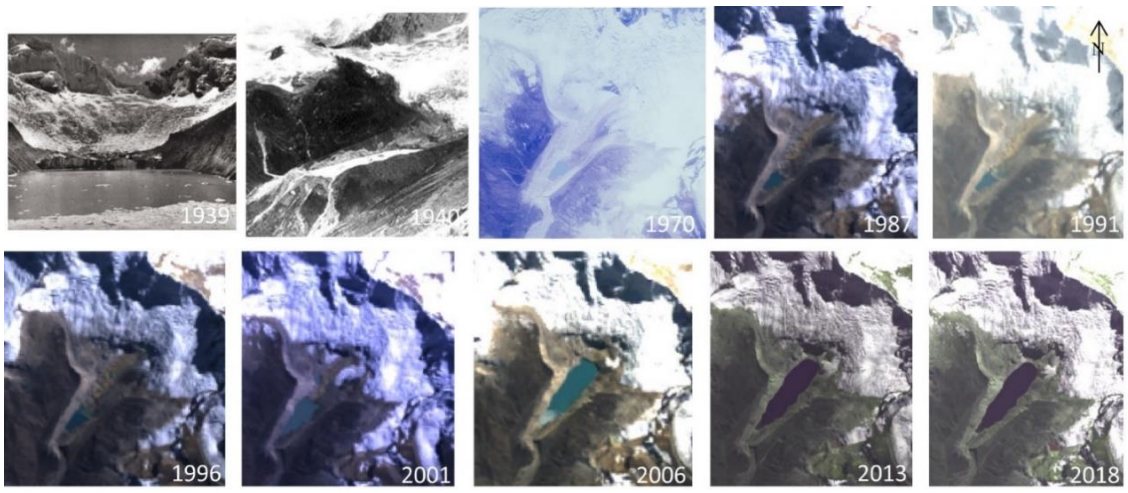


Figure 1: In situ (1939, 1940, 1970) and satellite (1987 onwards) images showing the evolution of Lake Palcacocha. This shows an over-spilling lake prior to the 1941 GLOF and then an initially minimal expansion followed by rapid lake growth due to the retreat of the glacier. The 1939 and 1940 images are from ref. [146], reproduced with permission from the family of Hans Kinzl, and the 1970 aerial photograph is from the USGS EROS Archive (https://earthexplorer.usgs.gov/fgdc/4660/AR6148000307153). Images from 1987 onwards are from Landsat 5 (1987-2006) and Landsat 8 (2013, 2018) downloaded from the USGS Earth Explorer (https://earthexplorer.usgs.gov). All images from 1970-2018 were taken in July / August.

Any evaluation of the contribution of anthropogenic greenhouse gas (GHG) and aerosol emissions to changing GLOF hazard must consider the whole causal chain. Our study has three parts. We evaluate: (1) the anthropogenic contribution to the observed temperature trend; (2) the role of this trend in the observed retreat of Palcaraju glacier (comprising numerical modelling of the glacier and a statistical comparison of the observed retreat with the natural length variability); and (3) the role of the glacier's retreat in reshaping the valley and the resultant change in GLOF hazard.

Attribution of Peru temperature trend to human activity

Globally, virtually all long-term temperature variations since the mid-19th Century have been attributed to external forcing[147]. Following the approach taken by ref. [148] and for Fig. 1.3 in ref. [149], we obtain local annual-mean temperature (see Methods) from the relevant grid cell in the HadCRUT4-Cowtan/Way (HadCRUT4-CW) dataset[150,151] (Fig. 2a). The HadCRUT4-CW trend is well supported by regional observations (see Methods). To quantify the anthropogenic contribution to regional temperature change, we regress the observed temperatures in HadCRUT4-CW onto the Global Warming Index (GWI)[148], an estimate of the anthropogenic contribution to global externally-forced temperature change, over the period 1940-2018 (see Methods). This yields region-specific scaling factors for GWI. Regional anthropogenically-forced warming is the product of this scaling factor and the GWI anomaly relative to 1880. For 1989-2018, it is found to be equal to 95% (85-105%, 5-95% range, all percentages rounded to the nearest 5%) of the observed temperature change over the same period. Uncertainty bounds are given by the inter-model range of regressions of the relevant grid cell in the control runs (with non-evolving pre-industrial conditions) of the Coupled Model Intercomparison Project Phase 5 (CMIP5) against GWI. Fig. 2a shows the observed temperature change for the HadCRUT4-CW grid cell containing Palcaraju glacier (black) and the temperature change in the same grid cell attributed to human GHG and aerosol emissions (orange). The correlation between regional temperatures and global anthropogenic warming with the estimated response to natural external climate drivers (solar variability and volcanic activity) is negligible.

Attribution of Palcaraju glacier retreat to climate change

The climate that a glacier experiences can be characterised by the vertical profile of its mass balance (i.e. accumulation minus ablation)[152]. We use a mass-balance profile (Fig. 2b) for Palcaraju glacier which, for the current climate, matches that observed on Shallap glacier (9°29'24" S, 77°20'24" W, a well-observed glacier approximately 10km away, with similar aspect to Palcaraju)[152]. The equilibrium line altitude (ELA, ~4950m in the current climate) denotes the altitude above which there is net accumulation and below which there is net

ablation. A simple and robust method of quantifying the impact of climate change on glacier mass balance is via geometric shifts of the mass-balance profile in response to temperature and precipitation changes[112,153–155]. The climatological precipitation is important for the shape of the mass-balance profile but, on century timescales, precipitation trends are small and temperature changes dominate mass-balance changes[112,156] (see also Methods and Supplementary Materials). Temperature changes are implemented through a vertical shift of the ELA based on the temperature lapse rate (here, approximately 5.5 K km^{-1}, giving an ELA sensitivity of approximately 180 m K^{-1})[112,157]. Detailed surface-energy-balance models show close agreement with this value for glaciers in the Cordillera Blanca[112,158].

Fig. 2b shows the decadal-mean mass-balance profiles produced in response to the HadCRUT4-CW observations since 1880. Tropical glaciers are characterised by steep vertical gradients in ablation, rendering them particularly sensitive to climatic perturbation[157]. Starting from an 1880 baseline, the point at which anthropogenic warming begins to emerge (Fig. 2a), a warming of 0.25 K and 1.3 K (the respective anthropogenic contributions in 1941 and 2019) raises the ELA by 45 and 235 m, respectively. At an elevation of 4600 m, characteristic of the early 20th Century ablation zone, these temperature changes increase the net ablation rate by 30% and 150%, respectively. Given the linear relationship between temperature and ELA, the human-induced warming (as previously stated) and change in ELA are equal to 95% of the observed temperature and modelled ELA changes, respectively.

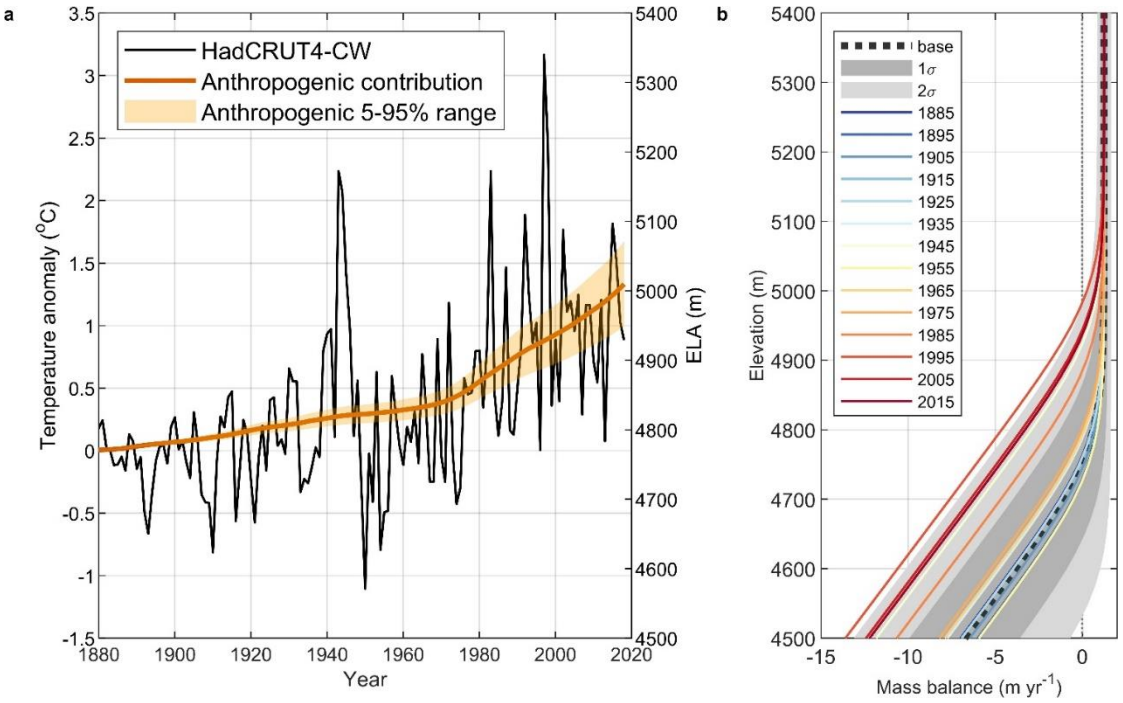


Figure 2: Regional observed and attributable temperature anomalies, and impacts on decadal-mean mass-balance profile. (a) Annual-mean temperature (HadCRUT4-CW) expressed as anomalies from 1850-1880 and the resulting ELA, and the contribution of anthropogenic forcing to the observed temperature change, with its 5-95% uncertainty ranges (shaded). (b) The resulting mass-balance profiles, plotted as decadal means, with the 1 and 2σ mass-balance range around the base profile shown in grey. The glacier's 1880 profile (Fig. 3) is in mass balance for the base profile.

Next, we use a numerical flowline model of ice dynamics (see Methods) to evaluate the thickness profiles of the glacier during its retreat, the interaction of rising ELA and the valley geometry, and the natural glacier fluctuations in the absence of climate change. In the absence of direct observations, we estimate that the 19th Century glacier terminus was situated 4.25 km along the flowline (see Methods). Uncertainty in the 1880 terminus position has no effect on present-day terminus position due to the geometry of the valley and the short response time of the modern glacier (Supplementary Materials, Fig. S1).

We model the response of Palcaraju glacier to regional annual temperature anomalies from three sources: HadCRUT4-CW (Fig. 2a), Berkeley Earth Land/Ocean observations[159], and the European Centre for Medium-Range Weather Forecasts' 20th-Century reanalysis (ERA-20C)[160].

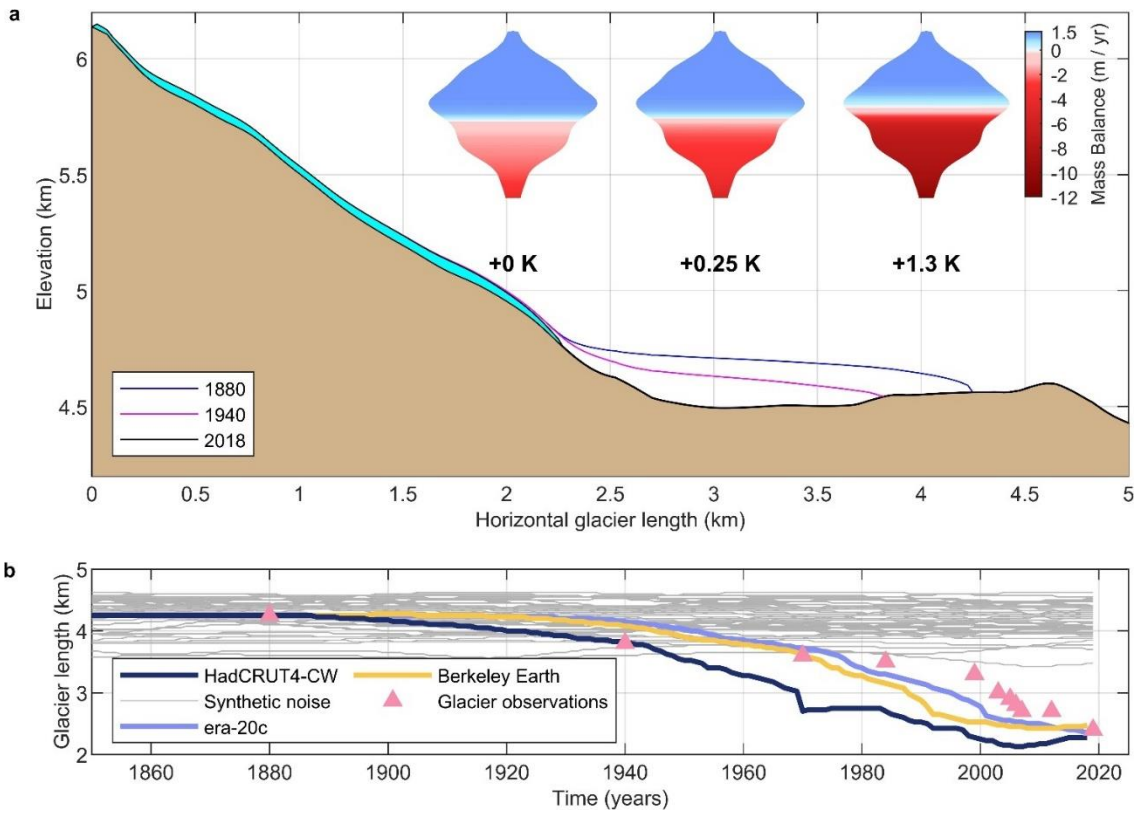


Figure 3: Mass-balance response to temperature change and modelled and observed retreat of Palcaraju glacier. (a) Longitudinal profile of Palcaraju glacier in 1880 (blue), 1940 (magenta) and 2018 (cyan) in the HadCRUT4-CW flowline model simulation; inset panels: idealised plan view of the glacier catchment with glacier width symmetrised about the flowline (approximately 5km across at its widest point) and the mass-balance profile for the baseline, +0.25 K and +1.3 K climates, corresponding to the anthropogenic warming in 1880, 1940 and 2019 respectively. (b) The modelled glacier length for three temperature timeseries (for which temperature changes begin in 1880, 1890, and 1900 for HadCRUT4-CW, Berkeley Earth and ERA-20C, see Methods), compared with the estimated 1880 glacier terminus position and observed 1940-2019 positions (interpreted from aerial imagery, shown as magenta triangles) and synthetic natural glacier length variability (grey lines). Retreat since 1850 is estimated to be 1825 m in observations, compared with modelled values of 1950 m (HadCRUT4-CW), 1750 m (Berkeley Earth) and 1875 m (ERA-20C).

For all three temperature time series, the numerical model gives an overall retreat similar to that observed (Fig. 3a, b), with the timing of the period of most rapid retreat being less predictable. The planform inset panels in Fig. 3a show the regions of the glacier with net accumulation in blue and ablation in red, highlighting that this non-linear retreat is a geometric consequence of the steep vertical gradient in mass balance and shallow slopes in the lower valley. Applied to the 1880 profile, a warming of 0.25 K causes net ablation below the ELA to increase by 40%, from 1.8 m yr^{-1} to 2.5 m yr^{-1}, which cannot then be balanced by the 1.1 m yr^{-1} of net accumulation above the ELA. For 1.3 K of warming, the average net ablation rate increases by 230% to 5.9 m yr^{-1}, and there is a 10% decrease in net accumulation

above the ELA to 1.0 m yr^{-1}. Rising temperatures have expelled the glacier from the lower valley.

In the observations and our simulations, the glacier retreats rapidly between lengths of approximately 3.0 and 2.7 km, taking 4 years in observations, and 1, 6, and 6 years in our modelled response to the HadCRUT4-CW, Berkeley Earth and ERA-20C timeseries, respectively. This period of rapid retreat is present in all simulations although its timing is sensitive to the warming history. It occurs in our model when thin ice above the slope break completely ablates, isolating a patch of stagnant ice on the lower slope. For the real glacier, the timing and nature of this retreat also depends on glacier-lake interactions and other processes not represented in our simulations. Our numerical model lacks lake-ice dynamics (including glacier calving and thermal conduction) and debris cover (see Methods), which likely affects the match between the transient evolution of the observed and modelled termini (Fig. 3b).

Could the observed retreat have happened without anthropogenic global climate change? Interannual climate variability will cause glacier fluctuations even in the absence of large-scale climate change[132,161]. The standard deviations (1σ) of regional annual-mean temperature and precipitation are approximately 0.5 K and 0.2 m yr^{-1}, respectively, with some interannual persistence likely due to the influence of El Niño (see Methods). Applying this climatic variability to the 1880 glacier profile in the flowline model gives interannual variability in ELA and mass balance of 100 m and 0.75 m yr^{-1} respectively (both 1σ) consistent with observations of similar glaciers[162]. We generate 10 kyr of synthetic climate variability and find centennial-scale length fluctuations with a standard deviation (σ_L) of 230 m (Fig. 3b, 4a). Fig. 4b and c show histograms of the 60-year and 140-year trends from the model output, compared with the observed retreat of Palcaraju between 1880 and 1940/2018, estimated at 550m and 1850m, respectively. In both cases the rates of observed retreat are larger than any of the model output, indicating a large-scale climate change is a necessary condition for the glacier's observed length change to occur.

We then quantify the change in glacier length that can occur from natural variability alone ($\Delta L|_{null}$), including uncertainty in the glacier response time (τ) and the standard deviation of the glacier length (σ_L). This analysis accounts for glaciers' amplification of the signal-to-noise ratio of climate change[39] (Fig. 4d, Equation 4, see Methods) and generates probability density functions (PDFs) for 60-year and 140-year length trends in the absence of climate change (Fig. 4e, f, see Methods). Given our assumptions, we conclude that it is virtually certain (>99% probability) that the observed retreat of Palcaraju glacier could not have occurred due to natural variability alone and therefore that the observed large-scale climate warming that we attribute to human influence is a 'necessary cause'[95] of the observed retreat both to 1940 and to the present.

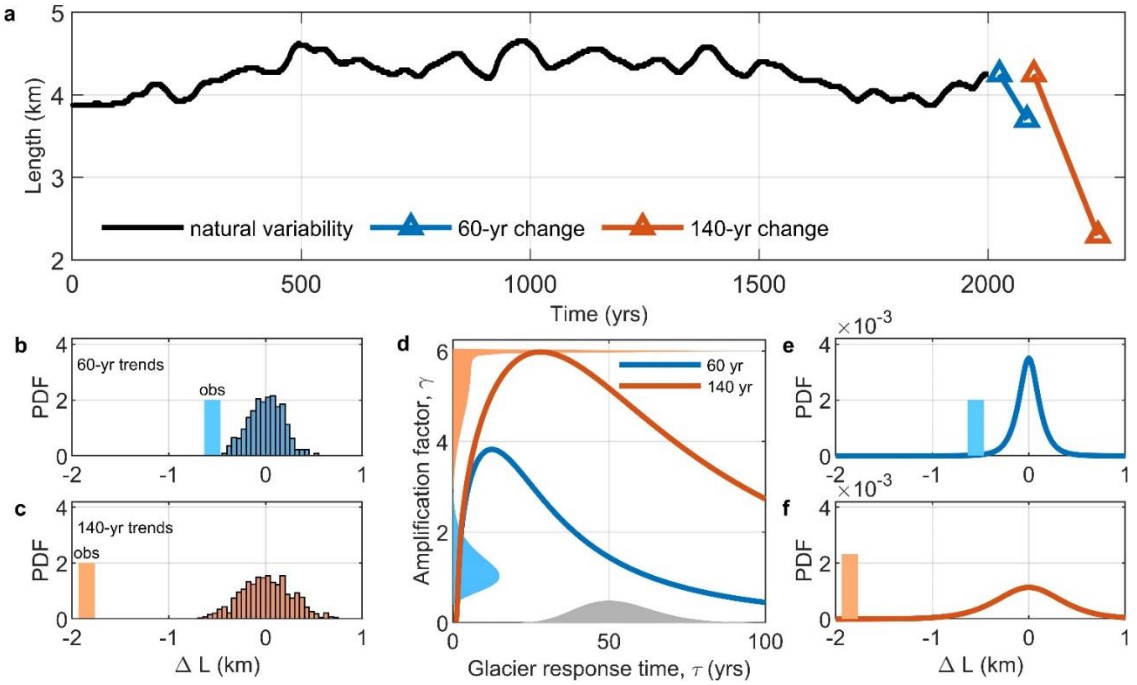


Figure 4: Analysis of the signal-to-noise ratio for Palcaraju glacier. (a) 2 kyr sample of glacier-length fluctuations occurring due to natural mass-balance variability alone (i.e. no temperature trend) taken from a 10 kyr simulation (black) and compared with the observed retreat of Palcaraju glacier 1880-1940 (blue), and 1880-2019 (orange). (b) Histogram of modelled 60-year length changes in the 10 kyr simulation of natural variability, as compared with the retreat observed between 1880-1940. (c) As (b), but for 140-year periods and compared with the observed length change between 1880 and 2019. (d) Transfer functions (solid lines) for calculating a glacier's amplification factor, (vertical axis, γ), for a 60-year (blue) and 140-year (orange) temperature trend, based on the glacier's 19th Century response time (horizontal axis, τ)[39]. We account for uncertainty in the value of τ in 1880 in the PDF on the horizontal axis (grey shading) and this gives rise to a PDF of values for γ for each of the time periods (shaded PDFs on the vertical axis). (e) The PDF for $\Delta L|_{null}$ in any 60-year period in a climate with interannual temperature variability but no climate change trend,

compared with the observed retreat between 1880-1940 (vertical bar). (f) As (e) but for a 140-year period and as compared with 1880-2019.

The PDF of $\Delta L|_{null}$ is symmetrical and centred over 0 m. Thus, over a 140-year period, the probability that the glacier would have extended is equal to the probability that it would have retreated, so our central (mean and median) estimate for $\Delta L|_{null}$ is 0 m. Consequently, our central estimate for the attributable fraction of the observed retreat to the observed temperature trend is 100%. Above, we find that anthropogenic warming equals 95% of the observed temperature change in 1989-2018.

Further, for the 1940 retreat not to have been the result of early anthropogenic warming (and be explained only by natural variability) at the 90% confidence level, the pre-anthropogenic equilibrium terminus must have lain within 200 m of the observed 1940 position (Fig. 4e, Fig. S2d). This is inconsistent with the early 20th-Century retreat observed elsewhere in the Cordillera Blanca and the glacier-length sensitivity to climate change required for the formation of the 17th-Century moraine (see Methods, and refs [139,163–165]). It would also require some unknown factor to counter the impact of the 0.25 K of anthropogenic warming on the mass balance (Fig. 3a inset).

Implications for GLOF hazard

Our results establish that the present geometries of the glacier and lake are the result of anthropogenic climate change. What are the implications for GLOF hazard? GLOF hazard is the product of the probability of a GLOF event occurring and the event magnitude[166]. Previous work has shown that although a catastrophic breach of the moraine dam is unlikely, the present GLOF hazard from Lake Palcacocha is very high due to the significant likelihood of an avalanche or landslide inducing a moraine-overtopping wave[6,143]. We use two ranking methodologies to evaluate changes in GLOF hazard from Lake Palcacocha between the present day and the 19th Century (see Methods and Tables S2 and S3). The ranking schemes indicate that the greatest influences on the increasing GLOF hazard are the steepness of the glacier snout, the growing lake area, and the glacier's retreat. The geometric method of ref. [167] was developed for settings where a moraine-overtopping wave is the likely GLOF

mechanism[167]. In line with previous application of this methodology to Palcacocha[137] we confirm that the present GLOF hazard is categorised as 'very high' and find that it has increased from 'medium' in the 19th Century. We compare these results with a geomorphological assessment methodology adapted from ref. [168]. It also presently ranks Lake Palcacocha in the highest GLOF hazard category, with the 19th Century GLOF risk categorised as 'medium'. As a result of this increase in GLOF hazard, Lake Palcacocha is considered a serious threat to Huaraz, compelling the local authorities to implement hazard mitigation measures[143].

The retreat of Palcaraju glacier, and resultant expansion of Lake Palcacocha, has increased both the probability and potential magnitude of a GLOF. In addition to the criteria assessed by the two hazard assessment methodologies employed here, permafrost degradation in response to rising temperatures can decrease slope stability, increasing the probability of rockfalls and landslides into glacial lakes. Further, the retreat of glaciers such as Palcaraju to steep mountain headwalls brings proglacial lakes closer to icy mountain flanks that have decreased stability due to glacier de-buttressing[168,169]. The increase in lake size since the 19th Century has also increased the likely GLOF volume, although neither methodology accounts for this change (the ref. [168] methodology includes area but the lake is already in the highest area class in the 19th Century).

The GLOF hazard posed by Lake Palcacocha to Huaraz has increased significantly due to the lake's expansion as Palcaraju glacier retreated and has now become a critical threat to Huaraz requiring engineered mitigation efforts. Given the assumptions in this three-step attribution, we find: (1) anthropogenic warming equals 95% (85-105%, 5-95% confidence interval) of the observed warming in 1989-2018; (2) our central estimate is that the retreat of Palcaraju glacier is entirely the result of this warming; (3) the retreat cannot be explained by natural climatic variability alone; and (4) this retreat has substantially increased the GLOF hazard for Huaraz. Despite some uncertainty about the 1880 position of the glacier terminus, our analysis also provides strong evidence of anthropogenic influence on the 1941 GLOF, a mid-20th Century humanitarian catastrophe. For the attribution of the overall retreat of

Palcaraju glacier, the 19th-Century position of the terminus is of lesser significance, and the present-day threat to Huaraz is a direct consequence of the anthropogenically-driven retreat of Palcaraju glacier.

Our analyses demonstrate the utility of risk-based approaches for evaluating the anthropogenic contribution to slow-onset, persistent hazards. The set of analyses presented in this paper could be applied to assess anthropogenic influence on GLOF hazard in any deglaciating alpine environment. Application of these methods in other locations would provide regional and global insight into human influence on present GLOF hazard and indicate how GLOF hazard may evolve under future climate change and where adaptation measures may need to be implemented.

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Author contributions

All authors planned the analyses which R.S.-S. and G.H.R. performed. All authors contributed to the interpretation of the results and to writing the manuscript.

Competing interests

The authors declare no competing financial or non-financial interests.

Methods

1. Temperature data, lack of precipitation trend

Given minimal seasonal temperature variations and consequent year-round ablation from tropical glaciers[152,157], we model the evolution of Palcaraju glacier in response to annual-mean temperatures. We primarily use the UK MetOffice HadCRUT4-Cowtan/Way (HadCRUT4-CW) dataset[150,151] as it provides continuous observations since 1850 and therefore a better pre-industrial baseline temperature for Peru than other observational datasets. Of the datasets considered, it also has an interannual temperature variability closest to the observed. The standard deviation of annual-mean temperature at the closest high-altitude meteorological station with an adequate record (the Mayor General FAP Armando Revoredo Iglesias Airport, 2,700m) is 0.62 K compared with 0.64 K for HadCRUT4-CW over the same period (1963-2018).

The baseline temperature was taken as the mean of 1850-1880. The observed warming between the baseline and most recent 10-year period (2009-2018) in HadCRUT4-CW is 1.01 K. Station observations in the Tropical Andes give temperature trends of +0.31 K/decade for 1969-1998 and +0.13 K/decade for 1983-2012[170]. Given these observed trends and the amplification of warming at higher altitudes[171] (the mean elevation of the HadCRUT4-CW grid cell is 1333 m) it is likely that our estimate of regional warming in the HadCRUT4-CW dataset is conservative. These factors do not affect the proportion of the trend attributable to anthropogenic influence. Further, surface-temperature simulations from the Hadley Centre regional climate model version 3P (HadRM3P) coupled to the global atmosphere model

HadAM3P from the weather@home distributed climate modelling system[172] give a temperature difference of around 1.5 K between the present and counterfactual (excluding human influence) climate (results not shown here).

A reduction in HadCRUT4-CW variability is evident prior to 1940 (Fig. 2a) and likely reflects greater reliance on interpolation over this period. The number of observations in the grid cell increases considerably from 1940, so this is the period regressed against the GWI. Regional anthropogenically-forced warming above the 1850-1880 baseline is calculated for 1989-2018 as equalling 95% (85-105%, 5-95% range) of the observed temperature change. This value displays slight sensitivity to the choice of the present-day period. If using a 10-year period, following ref. [149], regional anthropogenically-forced warming equals 120% (105-135%, 5-95% range) of the observed. The regression onto a global index assumes that the proportional contributions of anthropogenic and natural forcing to temperature change is the same at regional and global scales, justified by the absence of independent local factors that could create century-scale local climate trends. Such factors might include volcanic activity with effects localised to the Peruvian climate or significant local changes in albedo due to land-cover alterations over the past 150 years. No such factors are known[173].

We generate uncertainty estimates for the anthropogenic contribution to the temperature trends by regressing control simulations of 41 CMIP5 models (with no trends) against the GWI to calculate region-specific scaling factors for GWI. The product of GWI and these scaling factors creates a PDF of the degree that natural variability can project onto the observed temperature trend. The 5-to-95% range of this PDF is the uncertainty in our estimate of the anthropogenic influence. We note that temperature variability may be higher at the local scale than simulated in CMIP5. However, in the Cordillera Blanca, the magnitude of interannual variability in grid-scale and station data has been found to be similar over a 30-year period[174]. Further, even given an extreme assumption that local interannual temperature variability is double that of the CMIP5 grid cell, the 5-to-95% confidence range in the attribution statement broadens only slightly, from 85-105% to 70-120%.

We take annual precipitation values as the accumulation zone mass balance (for 2006-2008) from the nearby Shallap glacier[152]. Previous studies have found that most individual meteorological stations do not show significant trends in precipitation over the 20th Century[156], although some have found an increasing trend in Cordillera Blanca precipitation in recent decades[170]. This glacier is also comparatively insensitive to variations in precipitation (discussed further below) and we do not apply a precipitation trend here.

2. Interannual variability in temperature and precipitation, and persistence

The HadCRUT4-CW temperature dataset gives a standard deviation of 0.55 K in annual-mean temperature for between 1880 and 2018, and the Legates and Wilmot precipitation dataset[175] gives a standard deviation of 0.2 m yr^{-1} in annual-mean precipitation (1900-2010, with no significant trend)[175]. We test for interannual persistence in the climate data using autoregression modelling[176]. The precipitation data is consistent with no persistence (i.e., white noise) but, for the HadCRUT4-CW temperature data, the best-fit autoregressive process is a first-order (i.e., AR(1)) process with a lag-1 correlation coefficient of 0.32, indicating a decorrelation time of around a year. This persistence is likely associated with the influence of El Niño. Our synthetic time series of stochastic climate variability includes this persistence, which enhances the magnitude of natural glacier variability[39]. We also applied the autoregression model to an ensemble of 41 models of CMIP5 control runs and found lesser levels of persistence than observed in almost all models. Since interannual persistence enhances the natural variability against which we compare the retreat of Palcaraju glacier, the modelled persistence in CMIP5 suggests our incorporation of interannual persistence is a conservative assumption.

3. Vertical profile of mass balance

The influence of precipitation on the vertical mass-balance profile is incorporated in our modelling by using the observed mass-balance profile from Shallap glacier (with similar aspect to Palcaraju). Ref. [152] reports a vertical mass-balance gradient below the ELA (b_z^l) of approximately 3 m.w.e. (metres of water equivalent) per 100 m. The vertical mass-balance

gradient above the ELA (b_z^u) is approximately zero and the mass balance tapers smoothly to a constant of approximately 1.25 m.w.e. yr^{-1}. We join these two domains smoothly with a tanh function of altitude, z:

$$\frac{db}{dz} = b_z^l + \frac{(b_z^u - b_z^l)}{2}\left(1 + \tanh\left(\frac{z - z_{ela}}{\delta z}\right)\right) \quad (1)$$

Where z_{ela} is the ELA and δz is width of the transition zone (set as 200 m). $b(z)$ is then obtained by integrating Equation 1 downwards from the top of the domain. Ref. [152] reports an ELA for Shallap of 4985 m for 2006-7, and 4953 m for 2007-8, in close agreement with modern ELA we use for Palcaraju (Fig. 2a,b).

Tropical glaciers typically experience precipitation during the ablation season, and frequent changes in snow cover drive strong vertical gradients in albedo, and therefore mass balance[177]. The long ablation season of tropical glaciers also contributes to the strong vertical mass-balance gradient[157,177], which is nearly constant from year to year. Over two years of observations from the nearby Shallap glacier, ref. [152] report only a 3% difference in vertical gradient of ablation-zone mass balance, despite a 35% variation in accumulation. Consistent gradients can also be seen, for example, over 10 years at Uruashraju in Peru[157], with similar results found for Zongo glacier in Bolivia[178] and elsewhere in the tropics[179]. The near-constant year-on-year shape of the mass-balance profiles means that vertical and horizontal shifts of the mass-balance profile are a useful and efficient approximation to represent climate forcing[153–155].

4. Climate sensitivity of mass balance

Following refs. [155,157,180], the impact of temperature anomaly (T') is implemented by vertically shifting the mass balance by an amount $z' = T'/\Gamma$, where Γ = 5.5 x 10^{-3} K km^{-1} is the observed lapse rate[152,177]. We quantify the impact of a precipitation anomaly by adding a uniform anomaly to the mass-balance profile (a horizontal shift in Fig 2b). The steep mass-balance gradient in the ablation zone means that mass-balance variability is almost entirely due to temperature fluctuations. The interannual standard deviation of the ELA is 102 m with

precipitation and temperature variability included, and 100 m when precipitation variability is omitted. For the 1880 glacier profile (Fig. 3a) this translates to an interannual standard deviation in mass balance of 0.78 m yr^{-1} and 0.74 m yr^{-1}, respectively, when precipitation is, and is not, included.

Our calculations, provided in full in the Supplementary Materials, show that the ELA rises by 180 m for a 1 K temperature rise, in line with refs. [112] (180 m) and [157] (182 m). By contrast, a 10% increase in annual-mean precipitation raises mass balance by approximately 0.1 m yr^{-1}, equivalent to a 13 m decrease in ELA. Normalising results from other tropical glaciers elsewhere in the published literature to this same mass-balance perturbation gives ELA decreases of 16 m (ref. [112]) or 8 m (ref. [157]). These ELA changes are much lower than those which result from a 1 K increase in temperature. Temperature trends are much more important than conceivable precipitation trends for the ELA and mass balance of Palcaraju glacier.

We further note that the mass-balance sensitivity to precipitation is reduced by Palcaraju glacier's wet climate which means that, unlike some tropical glaciers, sublimation contributes only a small portion of the mass budget. Drier glaciers with significant sublimation tend to have higher precipitation sensitivity[181,182]. Ref. [152] reports that sublimation and evaporation accounts for about 10% of the ablation on Shallap glacier, consistent with the specific energy balance calculations of ref. [182].

5. Catchment geometry

The geometry of the Palcaraju glacier catchment was obtained from Google Earth[183]. A central-catchment flowline was estimated to obtain a longitudinal profile of topography. We replaced the lake surface in Google Earth with the observed lake bathymetry[138], and restored the topography of pre-1941 GLOF moraine at the end of the lake based on the reconstruction in ref. [138]. The resulting profile is shown in Fig. 3a. The profile does not remove the existing ice in the upper catchment, but as its thickness is only a few tens of metres[184], it has only a small effect on the profile. Ten approximately evenly spaced swaths along the profile were

measured for catchment width and symmetrised about the central flowline to produce the idealised planform catchment geometry, shown in the inset panels in Fig. 3a.

6. Numerical model

The numerical model is the same as that used in ref. [132], based on ref. [185]. The numerical model calculates ice flow from the shallow-ice approximation and Glen's Flow Law, and can be expressed as a pair of equations that are a function of time, t , and distance along the flowline, x:

$$\frac{dh}{dt} = \frac{1}{w(x)}\frac{d}{dx}\big(w(x)F(x)\big) + b(x) \tag{2}$$

$$F(x) = f_d \rho^3 g^3 h^5 \left(\frac{dz_s}{dx}\right)^3 \tag{3}$$

where h is ice thickness, w is flowline width, F is downslope flux, b is mass balance, f_d is the deformation constant, ρ is ice density, g is gravity, and dz_s/dx is surface slope. Equations 2 and 3 constitute a nonlinear diffusion equation, wherein the ice flux is a sensitive function of the glacier shape. This numerical model is a useful tool for evaluating the glacier profiles that are consistent with the landscape geometry and the rising ELA associated with the observed climate trend. It also provides a method to estimate the time scale of the glacier response. This response time controls both the magnitude of the natural glacier fluctuations and the glacier's response to a climate trend[51,186]. The flowline model does not incorporate the effect of debris cover, subglacial till, or lake-terminus dynamics including ice calving and thermal conduction. Glacier flow may also have altered the subglacial topography which, after the retreat, became the lake bathymetry. As such, the flowline model is not intended or expected to produce an exact simulation of the glacier's evolution.

To estimate the glacier-length response to natural climate variability, we generate 10 kyr of synthetic climate variability with the same statistical characteristics (variance and lag-1-year autocorrelation) as the observations. The resulting glacier-length fluctuations have a standard deviation of 235m.

7. Location of the 1880 terminus

In the absence of direct observations, we estimate the late 19th-Century terminus position, L_0. For our model, L_0 is the also the terminus position in equilibrium with the long-term average preindustrial climate. Centennial-scale fluctuations about this equilibrium position result from the glacier's response to interannual climate variability (i.e., Fig 4a)[132,186,187]. Our estimate for the magnitude of natural fluctuations is $\sigma_L = 235$ m. L_0 was necessarily set back from the main terminal moraine as previous work has shown the moraine formed in the 17th Century[140], and it has not since been overtopped by natural glacier length fluctuations. Reconstructions from elsewhere in the Peruvian Andes also indicate that glaciers had pulled back from their 17th-Century maxima by the late 19th Century[163]. It is also unlikely that L_0 was adjacent to the 1940 position: this would require larger natural variability for the glacier to have extended as far as the 17th-Century moraine, and these larger fluctuations would have taken the glacier further up the valley than the 1940 position, for which there is no evidence here or elsewhere in the region[140,163]. Glaciers with larger natural variability are also more sensitive to climate change[186], implying an even more sensitive system than that modelled here. Finally, some glacial retreat in the Cordillera Blanca was observed as temperatures began to rise in the decades prior to 1940[139,163–165]. We therefore set L_0 = 4250m. This places Palcaraju glacier's 19th-Century terminus approximately $2\sigma_L$ from both the 17th-Century moraine and the 1940 position which is consistent with the glacier fluctuating within this portion of the valley in the 18th and 19th Centuries, but not outside of it (Fig. 3a, 4a). Placing L_0 halfway between the 17th-Century moraine and the 1940 moraine is conservative: it allows for the largest magnitude of natural variability and is consistent with the known bounds of the glacier and our direct modelling of σ_L. If the 1880 position of the terminus is placed significantly closer to the 1940 front (say $L_0 < 4$ km) it also becomes difficult to reconcile that 1880 location with the approximately 40% increase in net ablation rates that accompanies the 0.25K of anthropogenic contribution to 1880 to 1940 warming, seen in the inset panels on Fig. 3.

8. Signal-to-noise ratio

A comprehensive uncertainty analysis of the change in glacier length that can occur from natural variability alone ($\Delta L|_{null}$) is possible. Ref. [39] used the property of glaciers' amplification of the signal-to-noise ratio of climate change, and that the amplification is greatest at intermediate glacier response times, to show that,

$$\Delta L|_{null} = \sigma_L \cdot \gamma(t_0, \tau) \cdot s_b|_{null} \quad (4)$$

where $\gamma(t_0, \tau)$ is an amplification factor that depends only on the duration of the change (t_0) and the glacier response time (τ), and $s_b|_{null}$ is the signal-to-noise ratio of the mass balance (b) due to the observed interannual variability (i.e. $\Delta b/\sigma_b$). The glacier response time equals the characteristic ice thickness (H) in the ablation zone divided by the (negative) net mass balance at the terminus (b_t) and affects both the amplitude and rate of change of length possible over a given time period, t_0. For the glacier's 1880 geometry, we estimate the response time as: $\tau = \frac{H}{-b_t} \approx 150\text{m}/3\text{m yr}^{-1} \approx 50$ yr. We have model estimates of τ and σ_L, but they are uncertain. We represent uncertainty in τ with a gamma function with 95% confidence bounds of 25 to 75 years (Fig. 4d). Similarly, for σ_L we give 95% confidence bounds of 115 to 345 m (Fig. S2c). $s_b|_{null}$ is taken from the observed interannual variability and follows the Student's t-distribution[39]. Through Equation 4, these PDFs yield PDFs for 60-yr and 140-yr length trends in the absence of a climate change (Fig 4e,f).

Equation 4 is derived in ref. [39] based on a three-stage model of glacier dynamics, whose parameters are governed by the glacier's geometry and climatic setting[186]. The model has been shown to accurately emulate glacier fluctuations in numerical models of ice-flow dynamics[186–188]. The three-stage model is linear, and although we do not expect linearity to apply over the whole valley profile, our goal is to characterise the much smaller fluctuations due to natural variability. The synthetic mass balance time series we apply to the numerical model (Fig 4a) is normally distributed, so the resulting glacier fluctuations are also approximately normally distributed, supporting the linearity approximation.

9. GLOF hazard assessment

We use two methods for identifying dangerous glacial lakes. The method proposed by ref. [167] was developed for assessing settings where the likely GLOF mechanism would be a moraine-overtopping wave induced by an ice avalanche, as is the case with Lake Palcacocha. GLOF hazard is quantified using the glacier area, the distance between the lake and glacier terminus, the slope between the lake and glacier, the mean slope of the moraine dam, and the glacier-snout steepness. Since Lake Palcacocha is in direct contact with Palcaraju glacier, we follow ref. [167] and use the gradient of the glacier snout, defined as the glacier area within 500 m horizontal distance from the terminus, in place of the slope between the lake and glacier. The area of the glacier is taken from the Global Land Ice Measurements from Space (GLIMS) database[189] (value is for 2015). The mean slope of the moraine dam before and after the 1941 GLOF (for the pre-industrial and present-day calculations, respectively) was taken from ref. [6], and the slope of the glacier snout from our model reconstructions of the 1880 and present-day glacier geometries. Our assessment gives the same numerical value for present GLOF hazard as ref. [137], using this methodology.

We supplement these calculations with an independent assessment adapted from ref. [168]. This methodology uses 11 weighted stability parameters, which relate to characteristics of the lake, lake surroundings and adjacent glaciers, and potential impact on downstream areas. Parameters are ranked according to influence on GLOF occurrence. We exclude two parameters from our analysis (glacier terminus slope and glacier velocity) since our analysis concerns present-day GLOF hazard and these factors are used to identify glacial lakes where future rapid expansion may occur, increasing the hazard. We recalculated the weight factors for the remaining nine parameters according to the method provided in ref. [168] (values provided in Table S3), which also instructs that flash-flood risk is set to zero if a debris flow is expected. We estimated the 19th-Century lake area as approximately 150,000 m^2 based on our modelling estimates of glacial retreat prior to 1941, and the estimated area of 303,000 m^2 immediately prior to the 1941 GLOF[2]. The lake area was 518,000 m^2 in 2016[145]. This method assesses hazard as 'high' if the four most important factors, or a combination of factors

which, combined, are equal to the sum of the weights of the four most important factors, apply.

Data availability: All climate data (observations and reanalysis) that support the findings of this study are publicly available from the KNMI Climate Explorer (https://climexp.knmi.nl/) except the Mayor General FAP Armando Revoredo Iglesias Airport station data which was downloaded from the Center for Climate and Resilience Research (University of Chile) Climate Explorer (http://explorador.cr2.cl/). All CMIP5 model data used in this study are available in public repositories, e.g. https://esgf-node.llnl.gov/search/cmip5/. The model data used here was stored on the Natural Environment Research Council's (NERC) designated data centre for the atmospheric sciences, BADC (British Atmospheric Data Centre). The Global Warming Index data are available from: https://www.globalwarmingindex.org/AWI/AWI_AR5_new_spreadsheet.xlsx.

Code availability: code will be available on request to the corresponding author.

6 Quantifying heat-related mortality attributable to human-induced climate change

Human rights arguments have played an increasingly prominent role in climate lawsuits.[23,91,190] Understanding the health impacts of climate change, and therefore how greenhouse gas emissions may compromise the enjoyment of human rights, is consequently of growing legal relevance. Moreover, robust evidence of the extent to which climate change is affecting human health can motivate policy action on adaptation and mitigation and inform evidence-based risk management. However, methods that synthesise epidemiological, physiological, and climate change attribution approaches are still under development.

Recent research sought to extend attribution analyses beyond physical hazards (extreme events and slow-onset processes, such as sea-level rise and glacier retreat) to the impacts of climate change. These impacts include both economic losses[29,35,191] and health impacts, including mortality from extreme weather events.[28,125,192,193] However, there remains a lack of a clear methodological framework for conducting such analyses. Existing literature focuses on a small range of health impacts, and is subject to substantial limitations. This article proposes resolutions to these limitations by effectively synthesising methods from epidemiology and climate science. We then apply the approach described to calculate heat-related deaths attributable to climate change in the Canton of Zürich (Switzerland) over 1969-2018. We find that heat-related deaths as a fraction of all-cause mortality rise substantially over this 50-year period, and are likely to continue to do so with further warming. Our analysis quantifies the avoided heat-related deaths due to the implementation of adaptation measures in recent decades. We also demonstrate that while existing literature and policy has focused primarily on heat-related deaths happening during heatwaves, a substantial burden of heat-related mortality also occurs at more moderate summer temperatures.

Quantifying heat-related mortality attributable to human-induced climate change

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The impacts of anthropogenic climate change remain largely unquantified. Here we detail and address limitations in existing methods for attributing health impacts to climate change, including the representation of the climate-health relationship, choices in calculating counterfactual temperatures, assessment of long-term trends and individual events, and estimation of the effects of adaptation. Applying these methods, we found over 1,700 deaths attributable to anthropogenic temperature increases in the Canton of Zürich (Switzerland) over 50 years. Changing exposures and vulnerabilities to heat, including due to adaptation, avoided over 700 deaths. Heat-related deaths peak during heatwaves but also occur throughout summer months and the fraction of deaths attributable to climate change is higher outside heatwaves. Our approach supports targeted adaptation measures, and the analyses described here could be adapted and

applied elsewhere to assess the effect of climate change on other health impacts or economic losses.

Significance Statement

Climate change is expected to have substantial effects on human health, yet there is only limited knowledge about the magnitude of these effects to date, or the effects that adaptation can have on reducing health risks from climate change. To quantify the impacts of climate change on health, epidemiological and climate-science methods need to be synthesized. Here, we develop an approach that facilitates more precise quantification of the effect of climate change on heat-related mortality and found that climate change is responsible for a large and growing burden of heat-related mortality over 50 years, in absolute terms and as a fraction of the total, despite adaptation measures, and that substantial climate-change-attributable mortality occurs within and outside of heatwave periods.

Introduction

Human-induced climate change causes substantial morbidity and mortality from increasingly frequent and intense extreme weather events, rising temperatures and sea levels, and altered seasonality[56,194]. These changes have direct physiological effects, shift the distribution of pathogens and disease vectors, reduce the yields and nutrient quality of food crops, and influence socioeconomic determinants of health. As global temperatures rise, the magnitude of associated health impacts is projected to increase further[67–69]. Studies quantifying the already-occurring effects of climate change on health can improve awareness of its impacts, inform adaptation decisions and political negotiations around loss and damage[195], and provide evidence for climate-related lawsuits[21], but remain limited in number, scope, regional coverage, and in the rigour of methods applied. No previous paper describes methods for attributing health impacts to climate change comprehensively, including the synthesis of climate attribution and epidemiological approaches. Here, we develop an approach for quantifying climate change effects on heat-related mortality in a specific

location. Methods described in this article can be adapted to assess effects of climate change on other health impacts or in other regions.

Widely-applied methods exist for quantifying the effect of climate change on weather[46] and climatic conditions on health[28,84]. Recent studies extended attribution analyses from assessing climate change influence on meteorological events to their economic and health impacts, including on heat-related mortality[28,125,192,193]. However, estimating the effect of climate change on current or historical health impacts is not a trivial task. Several methodological questions arise that have not yet been addressed sufficiently. These include how the climate-health relationship affects the approach for quantifying climate change impacts, how to account for adaptation and the various sources of uncertainty stemming from climate-science and epidemiological components of analyses, and what methods are best to quantify impacts resulting from single events and effects accumulated over longer periods of time.

We present a case study of the effect of climate change on observed heat-mortality impacts in the canton of Zürich (Switzerland) over 1969-2018 to illustrate method-related issues, and we argue that combining state-of-the-art climate-science and epidemiological methods can address the limitations of the approaches most commonly used at present. We use time-varying exposure-response associations to quantify the effects of adaptation in reducing populations' exposure to heat and conduct analyses that compare heat-related mortality attributable to climate change within and outside of heatwaves.

Probability and intensity-based approaches for health attribution

Climate change attribution studies quantify the effect of anthropogenic climate change on a meteorological event or trend in a climate variable relative to a counterfactual climate in which human influence is excluded. This counterfactual climate can be represented in multiple ways. One option is to quantify the relative likelihoods that an event greater than a threshold magnitude would occur in the present and counterfactual climates. Studies also assess how much less/more intense an event of observed probability would have been

without climate change, as we do here. These choices affect the representation of the climate-health relationship and the interpretation of the findings.

Probability-based assessments quantify the relative chance of exceeding a threshold magnitude with and without climate change. In practice, this approach represents the relative probabilities of the 'class of events' that meet or exceed the observed event's magnitude, rather than the specific event that occurred[83]. Such assessments also dichotomise exposure-response relationships: impacts are considered to occur at or beyond a threshold value and those that occur below the threshold are implicitly disregarded. Furthermore, because probabilities attributable to climate change reflect temperatures at least as high as the observed, probabilistic assessments represent the effect of climate change on more severe impacts than those that occurred[83]. However, temperature-mortality relationships are continuous above the minimum-mortality temperature, and heat-related deaths increase non-linearly with progressively higher temperatures. The overall mortality burden of moderate temperatures may be substantial since moderate temperatures occur commonly (Figure 1c).

If a study seeks to assess whether *any* heat-related deaths occur, the minimum-mortality temperature could be used as a threshold for a probability-based analysis, as is done in the epidemiological literature[196]. Otherwise, the effect of climate change can be assessed more accurately by comparing heat-related mortality under present-climate conditions and counterfactual temperatures using the state-of-the-art methods in climate epidemiology that account for the complexity (i.e., non-linearity and delayed effects) of the temperature-mortality relationship (time-series analysis, Methods, Figure 1a). We adopted this approach here.

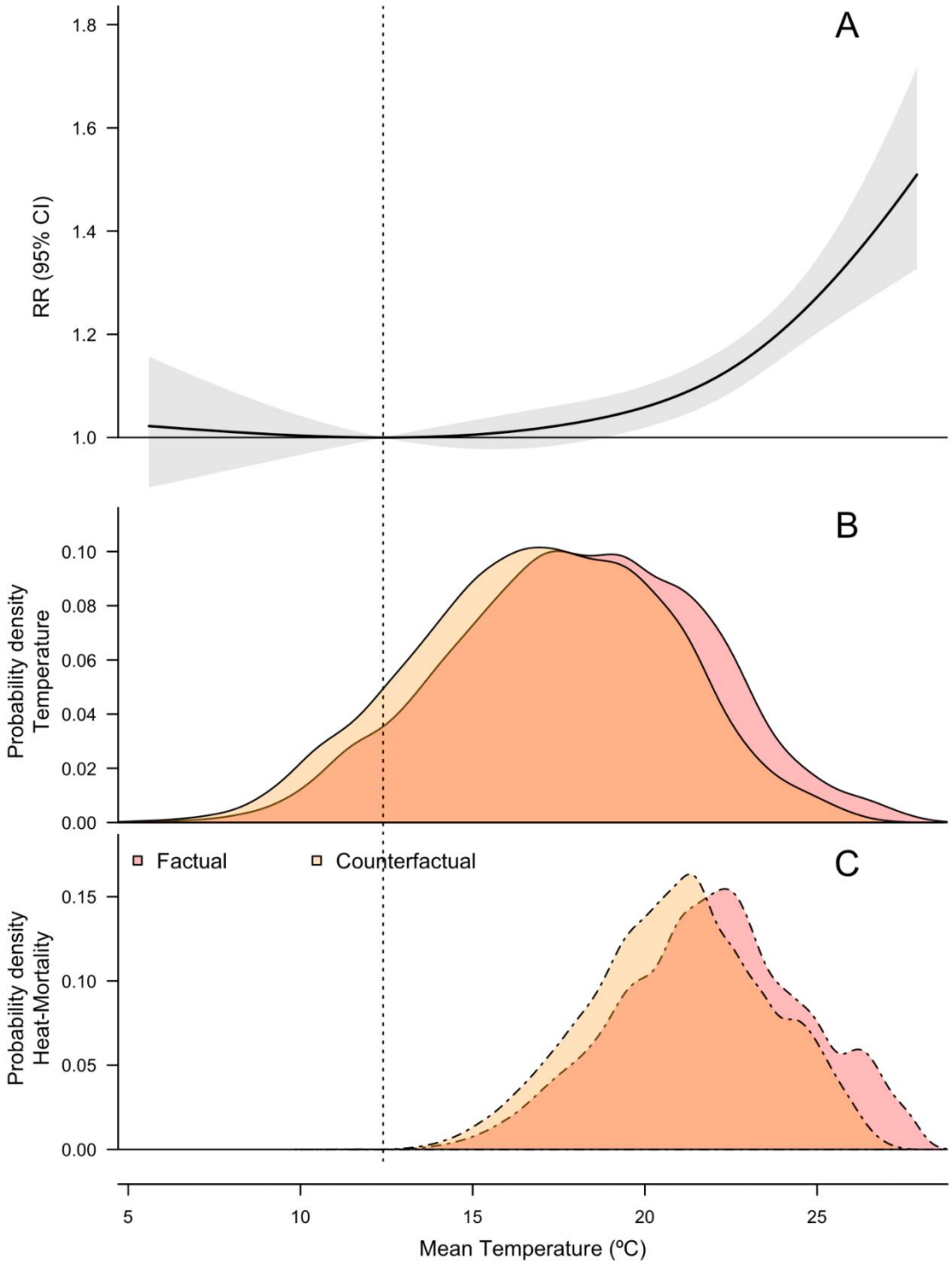


Figure 1: Exposure-response association for the Canton of Zürich, and probability density functions for temperatures under factual and counterfactual conditions, and the resulting distribution of mortality rates. a, exposure-response association calculated using observed temperature and mortality data for 1969-2018, and the 5-95% empirical confidence intervals (shaded area). **b**, PDFs of observed temperatures and a synthesis of model and observation-based counterfactual temperature timeseries (Methods). **c**, Proportion of heat-related mortality occurring at different temperatures. The vertical dashed line shows the minimum mortality temperature.

The intensity-based approach for attribution raises the question of how to estimate counterfactual temperatures. Previous research used bias-corrected climate-model (GCM) data to represent the historical climate, with anthropogenic and natural forcings, and a 'historical-natural' climate from which anthropogenic climate forcings are excluded[28]. However, day-to-day variability in GCM data does not align well with observed temperatures: days with highest temperatures differ between GCMs and observations (Figure S1). Consequently, in previous studies[28] it was more appropriate to use mean mortality by day of the year, as done in health impact projection studies[84], rather than observed data as the denominator to derive the daily heat-attributable fraction of deaths[28]. Mean values by day of the year retain seasonal patterns but do not represent the full variability of heat-related mortality. Peaks and troughs in daily mortality do not appear in averaged data.

We resolve this limitation by using observed temperatures to quantify heat-related mortality in the historical period and derive counterfactual temperatures by subtracting the anthropogenic temperature change for each day from the observations, based on climate-model and observation-based datasets. The attributable temperature change corresponds to the difference between factual and natural temperatures with return times equal to the observations, from daily GCM and reanalysis (observation-based gridded climate data) outputs (Methods). Because the observed pattern of daily temperatures is preserved, it is appropriate to use observed daily mortality to assess heat-related deaths. This approach accords greater confidence in calculating absolute values of heat-related mortality attributable to climate change, especially during heatwave periods.

Heat-related mortality attributable to anthropogenic climate change in Zürich between 1969-2018

We calculated climate-change-attributable heat-related mortality for the Canton of Zürich (Switzerland, population 1.5 million in 2021[197]) over 1969-2018 as the difference between that associated with observed and counterfactual temperatures (Methods). This requires daily temperatures under factual and counterfactual conditions, daily total mortality, and the exposure-response relationship between temperature and mortality risk.

To generate counterfactual temperatures, we calculated the quantiles of daily-mean temperature frequencies in station observations from Zürich for June – August 1969-2018, the period for which mortality data were available, fitted to a logistic distribution (Methods). For each day, we calculated the temperatures under historical (factual) and counterfactual conditions with return times equal to that calculated from the observations. To do so, we fitted daily-mean temperatures for the grid cell containing the Canton of Zürich from factual and counterfactual timeseries from an ensemble of models from the Coupled Model Intercomparison Project Phase 6 (CMIP6, Table S1) and observation-based datasets (reanalysis and station observations) to a logistic distribution. In models for which historical-natural simulations were unavailable, and for the observation-based data we applied a widely-used regression-based method for generating counterfactual temperatures[46] (Methods).

Daily counterfactual data were calculated by subtracting from station observations a temperature anomaly attributable to anthropogenic climate change, equal to the difference between factual and counterfactual temperatures in each model and observation-based dataset. Summer (June-August) warming attributable to anthropogenic influence increased across the study period, reaching 1-1.5 °C in 2009-2018 in model simulations, and slightly higher in reanalysis datasets (Figure S2).

The effect of ambient temperature on mortality is characterised by location-specific exposure-response associations [198]. We calculated the exposure-response association between observed temperature and all-cause mortality using an approach applied to assess past and projected relationships between temperature and mortality risk in a range of settings[28,199,200] (Figure 1a). We applied a distributed lag non-linear model to account for the non-linearity of the association and potential mortality displacement effect up to 7 days of lag (Methods). We used this association to estimate the temperature-attributable fraction of excess mortality, and calculated heat-related mortality for each day when temperatures exceeded the minimum-mortality temperature. Heat-related mortality was quantified using observed mortality for each day and the relative risk corresponding to the daily temperature.

Between 1969-2018, 6,217 (2,825-9,623, 5-95% empirical confidence interval) heat-related deaths occurred in the Canton of Zürich. In the counterfactual scenarios, heat-related mortality is 4,457 (synthesis value of model and observed datasets, 1,046-8,051), leaving 1,712 (276-3,329) deaths attributable to anthropogenic climate change (Table S3). This is equal to 27.5% of heat-related mortality and 1.4% (0.2-2.8%) of summer all-cause mortality in Zürich over this period (Figure 2b). Results by model and synthesis series are provided in Tables S3 and S4.

Previous research found that globally 0.6% of warm-season all-cause mortality (37% of heat-related mortality) was attributable to anthropogenic climate change over 1991-2018 (0.74% and 31.3% respectively for Switzerland)[28]. Here, heat-related mortality attributable to climate change was calculated as the difference between growing numbers of heat-related deaths occurring at increasingly common high temperatures and reduced numbers of deaths occurring at decreasingly common moderate temperatures (the difference between the areas under the curves in Figure 1c). Our results show that the proportion of all-cause mortality attributed to anthropogenic increases in temperatures rises as attributable warming increases (Figure 2c).

Trend attribution and accounting for adaptation

Our results find a substantial burden of heat-related mortality attributable to climate change. As in previous studies, we used a single exposure-response relationship derived from all observed mortality and temperature series representing the average vulnerability across the study period[28]. Using the full timeseries reduces uncertainty in the exposure-response association, especially in locations with a low number of observations. However, the temperature-mortality relationship evolves over time due to changes in demographic[201], physiological, behavioural, socioeconomic, and infrastructural factors[202]. A long daily-mortality dataset allows the use of a subset of the study period to assess changes in exposure-response associations over time. We use these changes to estimate the effect of adaptation on heat-related mortality by dividing all-cause summer mortality into three subsets: 1969-1985, 1986-2003, and 2004-2018 and derived exposure-response associations expressed as

relative risk (relative to the minimum-mortality temperature) for each period using daily-mean temperature observations (Figure S3).

We compared results obtained using a single (full-period) and time-varying exposure-response associations. Across the full analysis period, heat-related mortality attributable to climate change was 1.4% of all-cause mortality with both time-varying and constant exposure-response associations, supporting previous approaches[28]. However, using a constant exposure-response association underestimates heat-related mortality at the start of the timeseries, when the relationship between temperature and mortality risk is steeper, and overestimates heat-related mortality in the period since 2004, as risk was reduced due to adaptation, as detailed below (Figure 2a, Figure S3).

We quantify the effects of changing exposure and vulnerability of populations by using time-varying exposure-response associations to compare mortality in scenarios in which the exposure-response relationship derived for 1986-2003 is applied to 2004-2018 ('no adaptation') and in which the relationship is recalculated based on observed temperature and mortality over the period 2004-2018 ('adaptation'). In the 'adaptation' scenario, the exposure-response relationship reflects the changed sensitivity of the population to high temperatures over time. This could represent effects of changes in demographics, public health and healthcare systems, physiological adaptation, behaviour, access to blue and green spaces, and infrastructure. Our approach does not facilitate disaggregation of effects of specific measures. The Canton of Zürich has implemented limited measures for reducing heat impacts beyond those introduced at the Federal level[203], including information campaigns advising vulnerable populations on safe behaviour during heatwaves[204]. Because population ageing in Zürich has increased vulnerability to heat[201], decreases in the overall sensitivity of mortality to temperature are explained by adaptation-like changes irrespective of whether they constitute explicit responses to heat. We refer to these changes as 'adaptation'.

Under the 'no adaptation' scenario, in which these changes do not take place, an additional 738 deaths occurred over 1969-2018, relative to the 'adaptation' scenario when, in each case,

mortality was calculated based on observed temperatures. The change in the exposure-response relationship from 2004 onwards thus caused a 11% reduction in mortality over the period 2004-2018 relative to the mortality expected in the absence of these changes (Table S5). In both adaptation and no-adaptation scenarios, heat-related mortality attributable to climate change rose throughout the study period, with adaptation limiting this increase (Table 1, Figure 2*c*).

Scenario	Mean annual heat-related mortality attributable to anthropogenic climate change		
	1969-1985	**1986-2003**	**2004-2018**
Adaptation	19 (-24-48)	38 (1-80)	48 (22-94)
No-adaptation	19 (-24-48)	38 (1-80)	59 (30-110)
Single exposure-response	16 (-18-35)	34 (1-70)	49 (30-98)

Table 2: Mean annual heat-related mortality attributable to anthropogenic climate change for the three periods considered in the analysis and for the three exposure-response scenarios. In the 'adaptation' scenario, a time-varying exposure response association was calculated based on observed temperatures and mortality for each of the three periods. In the 'no-adaptation' scenario, the exposure-response association for 1986-2003 from the 'adaptation' scenario was also used for 2004-2018. In the 'single exposure-response' scenario, the exposure-response association was calculated based on observed mortality and temperature data from the full period (1969-2018). Central estimates and 5-95% confidence intervals were provided for the mortality values.

Our results suggest that, at least for Zürich, adaptation can reduce the burden of mortality associated with high temperatures. These results contrast with previous research that compared exposure-response associations for successive periods of time to evaluate England's heatwave plan and found very little change in the temperature-risk relationship following its introduction[205]. Nevertheless, substantial climate-change-attributable heat-related mortality continues to occur in Zürich. Under both 'adaptation' and 'no-adaptation' scenarios, attributable heat-related mortality constitutes an increasing portion of all-cause summer mortality at higher levels of regional warming (Figure 2c).

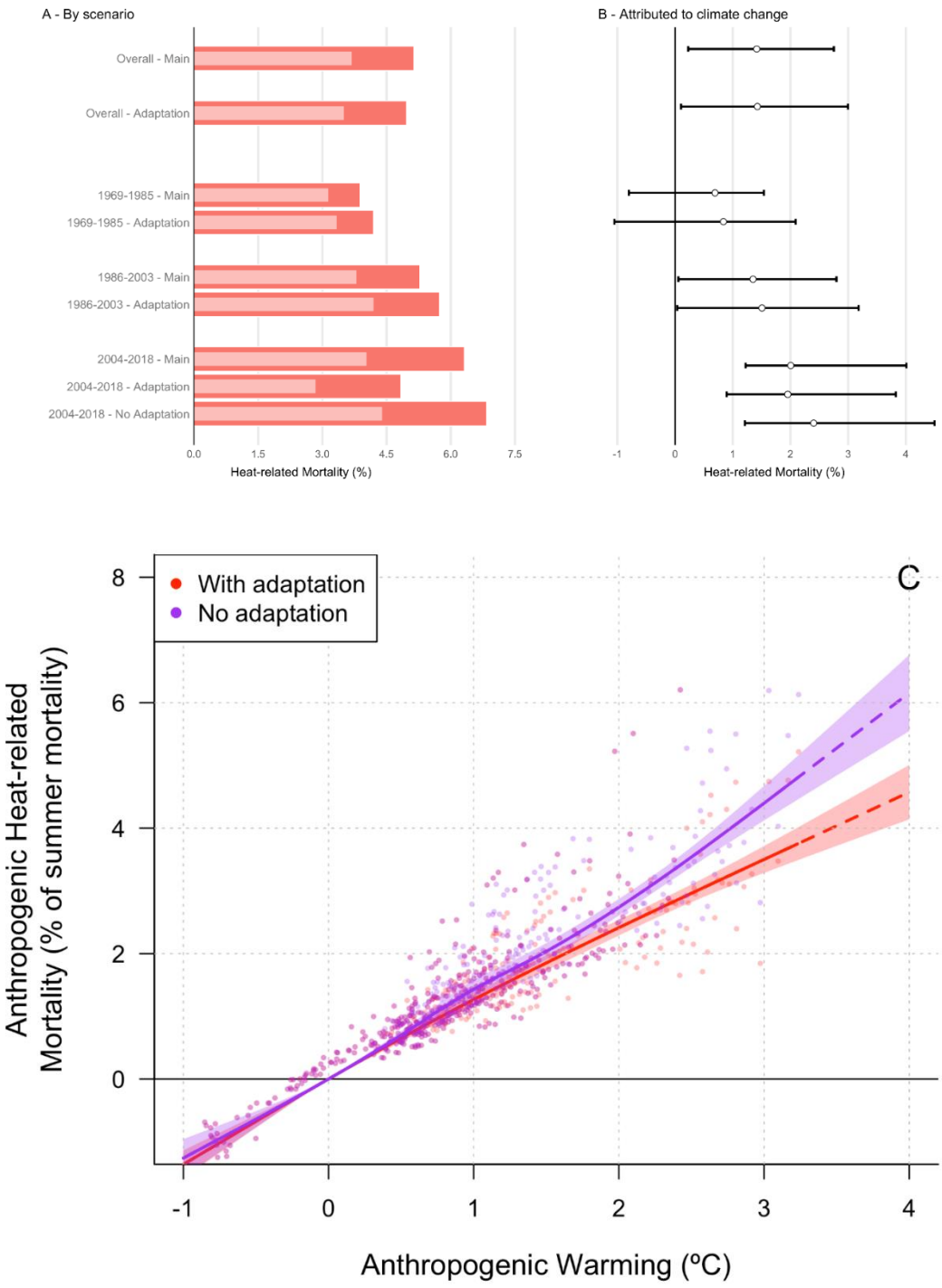


Figure 2: Heat-related mortality attributable to anthropogenic climate change for the Canton of Zürich. a, heat-related mortality as a % of all-cause summer mortality for 1969-2018 (overall exposure-response and 'adaptation' scenario only) and for each of the three time periods considered in the analysis. The 'no-adaptation' and 'adaptation' scenarios were identical for 1969-1985 and 1986-2003 so only 'adaptation' is shown. Dark red bars show values for the historical climate; light bars for the natural climate. **b**, as in panel **a** but showing the heat-related mortality attributable to climate change, with 5-95% empirical confidence intervals. **c**, the relationship between the regional temperature anomaly attributable to anthropogenic climate change (for Zürich) and the attributable heat-related mortality as a percentage of all-cause summer mortality for the 'adaptation' (red) and 'no-adaptation' scenarios (violet). The trend lines are calculated as a natural spline with 3 degrees of freedom, which produced the best fit to the data of the fits attempted (linear, and natural spline with

3, 4 and 5 degrees of freedom). Dashed lines show the continuation of the fit at temperature anomalies for which no data are available. We note that the 'no-adaptation' scenario only excludes the change in exposure-response association between 1986-2003 and 2004-2018, and that further adaptation would be expected to occur in response to further warming, reducing the sensitivity of mortality risk to temperature. The shaded area represents the 5-95% confidence intervals of the trend. All values given are the synthesis values of all models and observation-based datasets.

Attributable mortality within and outside heatwave periods

Previously-published methods could quantify heat-related mortality during heatwave periods alone[192,193,206] or assess climate trends over extended periods[28]. Probability-based assessments of heat-related mortality described above have only been applied to quantify impacts of climate change on heat-related mortality during an event of limited duration. Our approach to estimating counterfactual temperatures provides fungible results for both heatwaves and long-term analysis allowing long-term trend attribution to be aligned with an event attribution framework. This allows us to quantify the relative portion of heat-related mortality attributable to anthropogenic climate change within and outside of heatwave periods.

We apply this approach to Zürich. To assess heat-related mortality within and outside of heatwaves, we limited our analysis to the summer of 2018 and quantified heat-related mortality based on observed and counterfactual temperatures. Existing research found that human influence increased the intensity and likelihood of different aspects of the summer 2018 heatwave in Europe[207,208].

Across the summer of 2018, we estimate that 86 (55-114, 5-95% empirical confidence intervals) of 208 (114-304, 5-95% empirical confidence intervals) heat-related deaths in the Canton of Zürich are attributed to anthropogenically-driven temperature rise (i.e., 41%), based on the temperature-mortality relationship derived for 2004-2018. We define the heatwave period as 29 July – 10 August, the period of highest temperatures. Across these 12 days (13% of summer), 83 (46-115) heat-related deaths occurred, with 22 (-3-46) attributable to climate change (27% of heat-related deaths, Figure 3).

Because the temperature-mortality relationship is steepest at high temperatures, absolute values of climate-change-attributable heat-related mortality are highest on the hottest days. However, on days that are cooler but still above the minimum mortality temperature, climate change accounts for a larger proportion of the difference between the observed and minimum-mortality temperature than on hot days, and therefore a higher proportion of heat-related deaths. Our findings provide an empirical demonstration that climate change increases heat-related mortality on almost all summer days, and that while mortality peaks during heatwaves, heat-related mortality attributable to climate change also occurs outside of heatwaves.

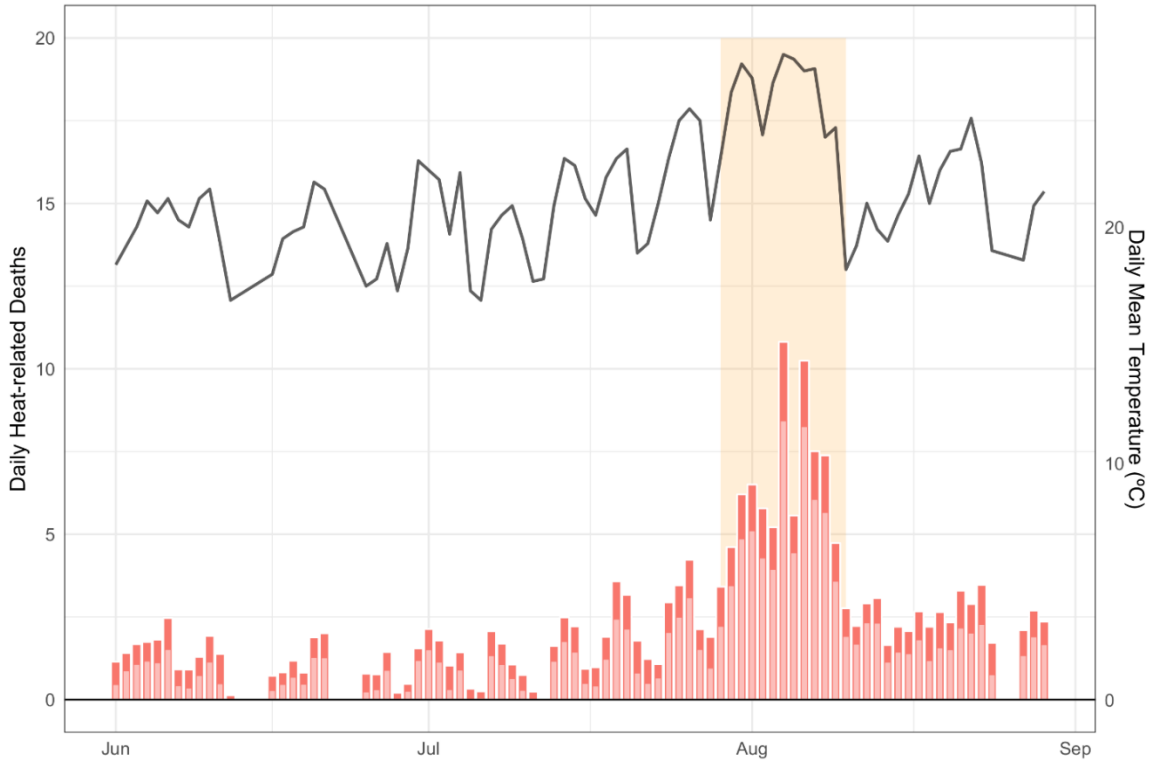


Figure 3: Observed daily-mean temperatures (black) and heat-related mortality (red bars) showing the portion attributable to anthropogenic climate change (dark red) for the Canton of Zürich, June – August 2018. Daily heat-related deaths are represented by the height of the bar, with the dark red segment corresponding to the number of daily deaths attributable to climate change. Tan shaded segment is the period defined as the 2018 heatwave in our analysis.

Discussion

Our climatological and epidemiological analyses yield three main findings. First, in the Canton of Zürich, 1,712 summer heat-related deaths were attributed to anthropogenic

climate change in 1969-2018. Previous research found that 90% of victims of heat-related mortality in Switzerland were 80 years old or older[201]. Second, temperature-mortality relationships were sensitive to adaptation. As daily temperatures increase, adaptation counteracted some heat impacts. Zürich enjoys advantages in its capacity to adapt to heat effects over many heat-exposed locations worldwide due to housing quality, high-quality health and social services, and economic prosperity. Nevertheless, substantial heat impacts were still observed. Empirical evidence for the effectiveness of adaptation is limited[209]. The results above provide improved understanding of the effectiveness of adaptation that could support policy and practice in future.

Third, heat-related mortality occurs at highest rates at the hottest temperatures. However, outside of heatwaves, the proportion of summer mortality attributable to anthropogenic climate change is higher (27% during the heatwave, versus 41% across summer 2018): climate change amplifies mortality throughout warm seasons. Analyses that focus on heatwaves alone will not capture the full effect of anthropogenic climate change on heat-related deaths.

We found that an average of 19 heat-related deaths attributable to anthropogenic climate change occurred each summer in 1969-1985, rising to 48 per summer since 2004. A simple method for allocating contributions to impacts that is commonly used in legal settings is the 'market-share approach' that estimates individual entities' contributions to losses as the product of the entity's proportional contribution to greenhouse gas emissions and the magnitude of the attributable impact[21]. Applying this approach here indicates that cumulative greenhouse gas emissions of each of the top six highest-emitting investor and state-owned companies[7] caused, on average, at least one additional death per summer in Zürich since 2004 (estimates for 1969-2018 are provided in Table S6). Similar findings would be expected for many other locations worldwide.

To conduct these analyses, we refined approaches for attributing health impacts to climate change and explained that probability and intensity-based framings have different application depending on the relationship between climatic hazards and their impacts. While

the method described here does not require additional data relative to the approach described in ref. [28], our analyses require data that are not available worldwide, including daily all-cause mortality and temperature observations. Limited availability and quality of granular health data and long-term climate observations present challenges for deriving location-specific relationships between climate variables and health outcomes, or in evaluating human influence on these climate variables.

Our results are consistent with previous analyses[28], demonstrate the scale of impacts already occurring because of observed climate change, and indicate the risk of worsening impacts under further warming, with global implications. The approach described can be applied elsewhere or adapted to evaluate the effect of climate change on other health risks. The methods employed here could be adapted to make greater use of reanalysis data in lieu of direct meteorological observations and estimating exposure-response associations based on available health data in conjunction with socioeconomic, institutional, climatological, demographic, and environmental information. These alterations could support evidence-based adaptation to climate change impacts on health, which disproportionately affect vulnerable groups, such as those living in poverty and urban areas[210]. These methods could also be refined to assess the effect of climate change on other health or economic impacts.

Methods

Climatological analysis

Methodological choices for climate change impact attribution. Meteorological attribution studies typically assess both the change in intensity attributable to human-influence on the climate for an event of given probability, or the change in probability of exceeding a threshold value. Previous studies assessed the health or economic impacts of climate change as the product of total impacts (for instance, heat-related deaths) and the fraction of the event likelihood (referred to as the 'Fraction of Attributable Risk', or 'FAR') for which anthropogenic climate change is responsible[29,125,191,192]. FAR quantifies the portion of the probability of exceeding a threshold event magnitude that is attributable to anthropogenic

climate change. As such, FAR may effectively quantify the effects of climate change when there is a threshold in the impact magnitude such that below-threshold climate hazards do not cause impacts.

However, as noted in the main text, if impacts increase continuously with the magnitude of the hazard, FAR-based assessments do not capture the effect of climate change on impacts occurring below the chosen threshold. Earlier, we explain that above the optimum, or minimum-mortality, temperature, heat-related mortality increases at progressively higher temperatures[28]. Therefore, quantifying the attributable mortality as the difference between mortality associated with observed temperatures and the temperatures that would have occurred in the absence of climate change most accurately captures the effects of climate change on heat-related mortality.

Constructing the counterfactual temperatures. To derive counterfactual temperature timeseries, we applied the extreme event attribution framework described in refs [46,85]. We detrended the observed temperatures by regressing against 4-yr smoothed global-mean surface temperature (GMST) using the NASA-GISS temperature dataset[211]. For each day of the study period, we calculated the return time of the temperatures in the observations fitted to a logistic distribution that represents the distribution of temperatures in the 30-year period centred on the year in question, or for data near the end of the timeseries, the longest period that could be centred on the data in question. This ensures that the estimated return times of daily temperatures are consistent with the climate in which they occurred, although we note that years near the end of the timeseries will be more affected by internal variability due to the shorter period used to estimate the mean of the temperature distribution.

The logistic distribution was chosen by fitting the detrended observed daily-mean temperatures with seasonal cycle removed (by subtracting the 30-day moving mean) to commonly used statistical distributions and applying the Anderson-Darling and Kolmogorov-Smirnov tests to identify the distribution that gave the best fit to the data. The statistical distributions attempted were the Generalised Extreme Value (GEV), Logistic, Normal, Rayleigh, and t Location Scale distributions. The seasonal cycle was reinstated

through the use of observations for the factual and in constructing the counterfactual temperatures.

We then calculated the change in daily-mean temperature attributable to anthropogenic climate change as the difference between the modelled daily-mean temperatures in the present (1989-2018) and counterfactual climates ($\bar{T}_{nat}$) in climate-model and observation-based (reanalysis) simulations. The temperatures under historical and historical-natural conditions were estimated as the temperatures with the same return time as the same day in the observations. Both observed and modelled / reanalysis timeseries were fit to logistic distributions and the distribution was shifted over time such that it reflected the temperatures of the 30-year period centred on the year in question. Model and reanalysis temperatures are taken from the grid cell containing Zürich (model temperatures are taken from an 18-member ensemble of CMIP6 models, Table S1). The difference in temperature caused by the difference between the mean elevation of the model grid cell and the station observations is corrected for using a lapse rate of -6.5 °C km^{-1}, consistent with summer lapse rates found elsewhere in the European Alps[212,213]. We then detrended the model and observation-based temperatures by regressing against each model's GMST and fit the resulting timeseries to the same statistical distribution as the observations.

We evaluated the models to assess whether the statistics of extreme heat in the models were consistent with those in the observations by comparing the scale and shape parameters of each of the model fits with that of the observations. Following ref. [46], the models for which the 5-95% confidence intervals of these parameters of the statistical fits overlapped with the 5-95% confidence intervals of the parameters of the observations, were initially selected for use in the analysis. Since only one model passed this evaluation step, and it is preferable to include multiple models to better account for systematic uncertainty in the model representation of the climate system, due to model structural biases and differing representations of physical processes, we expanded the range of parameter values used to evaluate models slightly (by 5% relative to the 5 and 95% confidence intervals). This increased the number of models passing the evaluation step to seven. All seven selected

models produce warming attributable to human influence that, at the end of the series lie within the range of the observation-based datasets (Figure S2).

We then calculated the attributable change in temperature for each day of the heatwave in all models that pass the evaluation step. We used the CMIP6-model ensemble to simulate the distribution of daily temperatures in the present day and in the absence of anthropogenic greenhouse-gas and aerosol emissions. We used daily output from historical (1850-2014) and SSP 5-8.5 (2015-2050) runs as transient simulations. For models for which both transient and historical-natural simulations (from the Detection and Attribution Model Intercomparison Project, DAMIP[214]) were available, the attributable change in temperature was calculated as the difference between the temperatures in the two sets of simulations, for return times equal to those in the observations. The return times of model temperatures were calculated using the same approach taken for the observations, with return times calculated based on a distribution representing the 30-year period centred on the year in question.

For the models for which historical-natural simulations were unavailable, the transient simulations were used and the distribution of daily-mean temperatures in the absence of human influence estimated by shifting the mean of the temperature distribution by the product of the change in GMST attributable to anthropogenic climate influence and a scaling factor. Global-mean human-induced warming is taken from the Global Warming Index, an estimate of the anthropogenic contribution to global externally-forced temperature change[148]. The scaling factor is dataset and region-specific and is the regression co-efficient (α) calculated in detrending the model/observational temperature data, which is the ratio between the gradients of local temperature observations and (4-yr smoothed) GMST from NASA-GISS[211] $\left(\alpha = \frac{dT_{obs}/dt}{dT_{GMST}/dt}\right)$. The same approach was also applied to the station observations and three climate reanalysis datasets: the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2)[215], Berkeley Earth Surface Temperature Project[216], and ERA5[217,218]. These two methods for calculating counterfactual temperatures are both commonly used in attribution studies when historical-natural simulations are available for some models but not others[46].

The regression-based method used for timeseries for which historical-natural simulations were unavailable can effectively account for the effect of anthropogenic influence on the climate on multi-decadal to centennial scales, it does not account for interdecadal variability. Consequently, this approach does not capture short-term influences on region-specific warming, such as lowered central European temperatures in the 1970s due to anthropogenic aerosol emissions[219,220] and so may overestimate temperature anomalies attributable to anthropogenic influence in this period, as seen in Figure S2.

This approach is also based on two assumptions. First, using GMST as a covariate to represent anthropogenic influence on local temperatures assumes that the long-term proportional contributions of anthropogenic and natural forcing to temperature change are equal at local and global scales, and therefore that there are no independent local factors that could create century-scale local climate trends. Such factors might plausibly include local changes in albedo due to land-cover alterations over the past 150 years. This is a widely-applied assumption in climate change attribution studies[46]. Therefore, we adopt this assumption here. Second, a common assumption in climate change attribution studies is that the trend in temperature extremes shifts with GMST, and that the scale parameter of the temperature distribution is unchanged over time. This is well supported for studies using large ensembles of model simulations[46]. Nevertheless, we tested this assumption by evaluating the sensitivity of attributable mortality to the values of the scale parameter. We iteratively fit 30-yr windows of detrended data to the statistical distribution and found that mortality is unchanged (<0.01% change) for a 1 standard deviation shift in the values of the parameters.

Epidemiological analysis

Our epidemiological analysis largely replicates the approach applied by Vicedo-Cabrera et al. (2021)[28] where the methods are described in full, with an important methodological adaptation. Instead of calculating mortality based on factual and counterfactual climate-model simulations, and mean mortality for each day of the warm season, we calculated heat-related mortality based on observed (summer) mortality and temperatures. This gives greater

confidence in our estimation of absolute values of heat-related mortality (Table S3) and allows us to account for changes in population. The values in Table S4 show the proportion of all-cause summer mortality attributable to the impact of anthropogenic climate change on summer temperatures, and are therefore unaffected by population change. We calculated counterfactual mortality using the counterfactual temperatures generated as described in the climatological analysis section, above.

Here we provide a brief overview of the epidemiological methods applied, noting elements of the methods specific to our study. We estimated the temperature-mortality relationship by conducting a time-series analysis with generalised linear models and quasi-Poisson regression using observed daily-mean temperature and mortality data during summer months (June-August)[28]. We modelled the temperature-mortality dependency with a distributed lag non-linear model that simultaneously accounts for delayed effects and non-linearity of the association, typically found in temperature-health studies. Specifically, the exposure-response dimension was defined with a natural spline with two internal knots placed in the 50th and 90th percentile of the summer temperature distribution. The lag-response dimension also included a natural spline with two internal knots equally spaced in the log scale and up to 7 days of lag. The time-series model included a natural spline of day of the year with 4 degrees of freedom and an interaction by year, and a natural spline of time with 1 knot every 10 years to control for both seasonality and long-term trends. The specifications of the time series model and the definition of the cross-basis function of temperature are the ones described in Vicedo-Cabrera et al. (2021) and have been extensively used in previous assessments[28,196,221,222]. We did not control for air pollution and/or humidity since previous assessments suggested that the role of these variables as confounders was negligible[72,196]. The analysis was performed across the whole study period (June-August 1969-2018) to obtain the overall temperature-mortality association, and by subperiod to obtain the corresponding association estimates.

We quantified the mortality attributed to heat using the observed mortality and the risk estimate corresponding to the mean temperature each day, for the observed and

counterfactual series, using the method described elsewhere[223]. Previous epidemiological research showed that deriving such associations using time-series analysis of daily-mean temperatures and daily all-cause mortality effectively describes climatic influence on mortality [70,196]. We then sum the daily temperature-related deaths of the days when mean temperature (both in the observed and counterfactual series) was above the temperature of minimum mortality (i.e., temperature value for which the mortality risk is minimum). In doing so, we considered the risk contribution of the preceding 7 days, following findings that the effect of heat on mortality lasts for up to a week[204,224]. We derived ensemble estimates for the counterfactual scenario as the average across mortality in each counterfactual temperature timeseries. We quantified the uncertainty of the estimates by generating 1,000 samples of the coefficients defining the exposure-response association through Monte Carlo simulations, assuming a multivariate normal distribution. We derived the 95% empirical confidence intervals (eCI) from the resulting distribution, corresponding to the 2.5th and 97.5th percentiles. The eCI of the ensemble estimates of the counterfactual scenarios (i.e., by averaging across the single-series estimates) were estimated by combining the single-series distributions. Thus, in this way we account for both uncertainty of the exposure-response function and the variability across the different counterfactual series.

The mortality attributable to human influence is then quantified as the difference between the observed mortality due to heat (i.e., using the data from station observations) and the corresponding burden estimated with the counterfactual series. The computation was performed across the whole study period, by subperiods and during summer 2018 and the 12 days of the heatwave in that summer. Daily-mean temperature is widely used as a determinant of heat exposure in calculating temperature-mortality relationships[28,84,196,225].

Data availability: Temperature observations for Zürich / Fluntern can be downloaded from the KNMI Climate Explorer at http://climexp.knmi.nl/ (last accessed: 19.08.2022). ERA5 reanalysis data are openly available from the Copernicus Climate Change Service at https://cds.climate.copernicus.eu/#!/home (last accessed: 22.04.2022), MERRA2 from NASA Goddard Earth Sciences (GES) Data and Information Services Center (DISC) at

https://disc.gsfc.nasa.gov/datasets/M2TMNXSLV_5.12.4/summary (last accessed: 22.04.2022), and Berkeley Earth from http://berkeleyearth.org/data/ (last accessed: 26.08.2022). All the CMIP6 model simulations are obtained from the CEDA Archive-part of NERC's Environmental Data Service at https://catalogue.ceda.ac.uk/?q=CMIP6&sort_by=relevance&results_per_page=20 (last accessed: 25.08.2022).

Mortality data will be made available at the official data repository of the University of Bern (BORIS) on publication.

Code availability: Code for the analysis of climate data will be available upon request to the corresponding author. Code for the epidemiological analysis will be made publicly available on GitHub on publication.

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Author contributions R.S.S., A.M.V.C., S.L., F.O., and K.E. conceived the analysis which R.S.S., A.M.V.C., and S.L. performed. R.S.S. and A.M.V.C. drafted the manuscript and all authors contributed to revisions.

Competing interests The authors declare no competing interests.

7 Conclusion

Previous work recognised the potential of attribution science to support causal claims in climate lawsuits.[15,17–20,22,36,226,227] That attribution science is legally relevant is therefore not a novel claim. However, attribution science remains a relatively young field of scientific inquiry and its use in the courts is at an even earlier stage. This work has sought to address some of the outstanding challenges associated with the interdisciplinary endeavours of understanding how well the methods and findings of attribution science align with legal reasoning and the use and interpretation of attribution science in past legal proceedings. Future research could respond to new scientific developments and changing legal norms to further understanding of how scientific insight and legal reasoning can be aligned most effectively.

Attribution science creates opportunities for legal action to be brought to prevent impacts of climate change, or to seek compensation for harms that result from these impacts. Legal action also creates demands for new insight from the scientific community, generating questions and research agendas that require scientific innovation to resolve. This thesis sheds light on the opportunities brought by attribution science, and responds to emerging scientific questions regarding the effects of climate change that have arisen in the courts.

7.1 Legally-relevant attribution-science research

Section 4 reviewed the state of play of the use of attribution science in climate lawsuits. We found that while attribution science has been recognised by legal scholars as holding the potential to strengthen causation arguments in climate lawsuits for some time, there remains substantial potential for further engagement of lawyers with these scientific developments. Relatively few lawsuits have reached the merits stage to date, at which point causation claims would be more closely interrogated by courts. However, evidence on causation may also be considered to establish standing to bring the case. In some claims, a lack of causation evidence had served as an obstacle to their success. Supporting climate lawsuits with state-of-the-art scientific insight could increase the likelihood of successful outcomes.

These findings demonstrate the contribution that judicious use of climate science can make to strengthening future legal claims. As the courts have assumed increasingly influential positions in efforts to address the impacts of climate change, ensuring that claims are well-grounded scientifically is essential. To better integrate scientific insight into legal reasoning, jurisdiction-specific assessments of attribution and causation would provide judges with a framework for assessing scientifically-informed causal claims. This research would also aid litigants in crafting improved arguments that are well-aligned with developments in climate science. Moreover, there is an ongoing need to harmonise legal and scientific arguments to strengthen the use of attribution science in court. Future research might investigate how attribution science can support successful legal claims in a range of jurisdictional contexts, and focus on different areas of law.

Climate lawsuits and international negotiations on loss and damage have raised the question of the specific contributions that individual entities – be they companies or countries – have made to climate change impacts. Attribution science methods can be deployed to quantify the contribution of anthropogenic greenhouse gas emissions as a whole to climate change impacts. Recent studies have also evaluated the contribution of individual emitters.[30–33,35,81] In section 4, the potential value of evidence of this type was noted. While attribution to individual emitters of greenhouse gases, rather than climate change as a whole, is unlikely to be necessary in all cases, there are incidences in which being able to cite evidence of this type would strengthen legal claims or challenge inaccurate assertions that conducting such analyses would not be possible.

However, when conducting studies of this type, choices are made relating to methods or the framing of results. These choices include how the effects of short-lived climate forces (such as methane) are accounted for, or the approach used to quantify the marginal effect of individual emitters' greenhouse gas emissions. These are not purely scientific questions but involve determinations that can substantially affect results. For instance, recent literature suggested that the contribution of short-lived climate pollutants should be accounted for on the basis of changes in the rate of emissions and therefore the present-day warming effect of

those emissions.[228] Thus, reductions in the rate of short-lived climate pollutants are considered to have a (net) cooling effect. Alternatively, an emission of short-lived climate forcings can be seen as creating a (time bound) increase in temperature – and therefore climate change impacts – that would not have occurred in the absence of those emissions.[229] Choices such as these ultimately concern the interpretation of scientific findings, and are not themselves questions that have a clear scientific basis for determining their answers.

It is likely that issues such as the approach used for accounting for the effects of emissions of short-lived climate pollutants and the framing of attribution findings will come under greater scrutiny or become a site of scientific contestation as climate lawsuits proceed further in the courts. There is a need, therefore, to understand how such choices can be aligned with logics of causation, including in law. This would facilitate differentiation between contrasting interpretations of scientific findings, support the development of legal arguments by litigants, and aid judicial adjudication when contrasting interpretation of science is offered.

7.2 Impacts of climate change on cryosphere hazards

Scientific developments have facilitated assessment of the contribution of climate change to impacts that claimants argue derive from greenhouse gas emissions. Section 5 presents the first study of the role of climate change in the hazard of a glacial lake outburst flood in the context of an ongoing lawsuit (*Lliuya v. RWE*). This required exploration of a causal chain that spanned anthropogenic influence on the global climate, to the effect on regional temperatures, the consequent retreat of the Palcaraju glacier, in the wake of which Laguna Palcacocha has expanded, to the ensuing changes in flood hazard from the lake. The analysis concluded that 95% (85-105%, 5-95% confidence intervals) of observed warming in the region surrounding the Palcaraju glacier could be attributed to anthropogenic influence on the climate over the industrial era. We then considered the observed retreat of the Palcaraju glacier and found that it could not be explained by natural climate variability alone, at the 99% confidence level; moreover, our central estimate was that the retreat of the Palcaraju glacier since 1880 was entirely attributable to observed temperature change. Finally, we

concluded that this anthropogenically-driven glacier retreat had substantially increased the risk of a glacier lake outburst flood for the city of Huaraz.

This analysis suggests that increasing glacial lake outburst flood hazards that arise or increase as glaciers retreat – as they are worldwide[129] – are impacts in which climate change is playing a substantial role. Recent research also found that virtually all industrial-era glacier mass loss can be attributed to anthropogenic climate change.[40] Given the substantial risks that glacial lake outburst floods pose in deglaciating alpine regions, further research might build on the analysis described in section 5 of this thesis, recent regional assessments of the development of dangerous glacial lakes,[230] and inventories of past outburst floods[231] and adapt our methods to develop regional or global-scale assessments of changes in outburst flood hazards attributable to climate change. Such analyses would confirm the indication provided by this research that increased glacial lake outburst floods can generally be attributed conclusively to anthropogenic climate change.

7.3 Impacts of climate change on human health

Section 6 is concerned with an emerging area of legally-relevant attribution science. In this article, we explored how attribution science methods can be refined to extend analyses beyond physical hazards alone – the temperature of a heatwave or the strength of a storm, for instance – to the health impacts of these conditions. Such analyses are of particular importance for the growing number of rights-based climate change claims being brought before courts worldwide.[23,190] This article refined approaches for synthesising epidemiological and climate-science methods and offers three key advances. First, the methods described in this article allow us to provide robust quantification of heat-related mortality attributable to anthropogenic influence on the climate in absolute terms, through the use of observed daily mortality and temperature data to quantify heat-related deaths. Second, the approach bridges methods applied to evaluate both long-term trends and extreme events, providing adaptation-relevant insight into the contribution of climate change to heat-related mortality both within and outside of heatwaves. Previous studies could provide long-term assessments or evaluate individual heatwaves.

Finally, by deriving time-varying exposure-response associations, we were able to evaluate changes in vulnerability and exposure to heat over time, and therefore the impact of adaptation measures. This analysis provides general support to previous studies (e.g. ref. [28]) that used a single exposure-response association derived from all available daily mortality and temperature observations when applied to quantify heat-related mortality over the full duration of the observed period. However, substantial secular changes in the temperature-mortality association are found. These changes more than counteracted the known effects of population ageing, and we concluded that adaptation had prevented at least 700 heat-related deaths between 2004-2018 in the Canton of Zürich.

The methods developed in section 6 of this thesis could be adapted in future research to evaluate the effects of climate change on heat-related mortality in other locations, including those with reduced climate or health data availability, and on other impacts of climate change on health. Such impacts might include vector-borne diseases such as dengue, or other direct consequences of exposure to changing mean or extreme weather conditions. Nevertheless, these results indicate the vast scale of heat-related mortality that is already occurring due to climate change.

7.4 Concluding remarks

Climate change attribution science has revolutionised our understanding of the effects of greenhouse gas emissions. The findings of attribution studies demonstrate clear links between anthropogenic influence on the climate and physical manifestations of climate change. Increasingly, these assessments can be extended to evaluate the social, health, economic, or infrastructural impacts of physical hazards. The ability to trace climate change impacts to their causes has opened up new avenues for legal and policy responses to climate change. Attribution science is likely to play an increasingly prominent role as lawsuits regarding the impacts of climate change advance beyond the procedural hurdles encountered in the opening salvo of climate damages litigation. Moreover, recognition of the need to manage the losses and damages associated with climate change is growing. Understanding

what these losses and damages are becomes essential, and attribution-science methods may also be deployed to this end.

The physical manifestations of climate change are increasingly subject to legal scrutiny. Past legal claims were found to often not use location-specific attribution evidence, but the research described in this thesis demonstrates the potential of scientific insight to strengthen claims. The nature of impacts in question in specific lawsuits produce particular demands for research. Moreover, for scientific evidence to be leveraged most effectively in court, lawyers need to understand how developments in climate science align with legal causation frameworks. It is clear that the state of the science should in principle be sufficient to establish causation in many settings. However, litigation-relevant science is not always available in the published literature. Many claims concern impacts that could be evaluated with existing methods. Others, including those considered in this thesis require refined methods to resolve causation questions.

The two scientific analyses conducted in this thesis are location-specific, concerning glacial lake outburst flood hazard in the Peruvian Andes and heat-related mortality in the Canton of Zürich, Switzerland. While care needs to be taken when extrapolating these results to other locations, existing literature indicates that similar results can be expected in many locations worldwide. Attributable increases in warm-season temperatures and hot extremes have been found in most regions[77] and existing attribution research on glacier retreat found a substantial role for climate change in many alpine regions.[39] Local factors may cause deviations from what is otherwise a largely globally-consistent picture. Long-term changes in local albedo through land use or land cover change, for instance can alter local climate response to global warming. Moreover, evolving glacial lake outburst flood risk is sensitive to factors that are specific to individual valleys, including the existence and integrity of a terminal moraine dam, gradient of the underlying bedrock, and presence of mechanisms that could trigger an outburst flood, such as an avalanche or landslide risk.

Research in attribution science has shed light on a process that cannot be observed with the naked eye in which greenhouse gas emissions lead to global warming, which manifests in

physical impacts experienced worldwide by individuals, communities, ecosystems, and economies. The harms of climate change are already occurring on a vast scale, only a fraction of which have been captured by existing attribution studies. The process by which emitting greenhouse gas emissions causes harm is mediated by the global climate system; scientific insight reveals that notwithstanding the complexity of this process, it is still possible to demonstrate that greenhouse gas emissions result in identifiable harms.

Leveraging these scientific developments, climate change litigation can accelerate reductions in greenhouse gas emissions, and hold emitters responsible for the consequences of their actions. Successful cases, through the development of powerful precedents may induce rapid and disruptive changes that accelerate climate action and ultimately elicit policy responses that were hitherto lacking.

The use of the law to address climate change is fast evolving, fuelled by innovation in legal arguments, as well as shifting policy, funding, and scientific contexts. The changing context in which climate lawsuits are brought creates new opportunities for legal intervention, and alters case outcomes. Equally, efforts to creatively apply the law to address climate change fosters a radically innovative research environment that demands scientific progress to generate legally-relevant insight. Science facilitates climate litigation, but litigation also presents opportunities for scientific impact that is of as much benefit to science as it is to the law.

8 Appendices

8.1 Further publications supporting this thesis

Peer-reviewed publications

Otto, F. E. L., Minnerop, P., Raju, E., Harrington, L. J., **Stuart-Smith, R. F.**, Boyd, E., James, R., Jones, R., & Lauta, K. C. (2022). Causality and the fate of climate litigation: The role of the social superstructure narrative. Global Policy, 13(5), 736–750. https://doi.org/10.1111/1758-5899.13113

Clarke, B. J., Otto, F. E. L., **Stuart-Smith, R. F.**, & Harrington, L. J. (2022). Extreme weather impacts of climate change: an attribution perspective. Environmental Research: Climate, 1(1), 012001. https://doi.org/10.1088/2752-5295/ac6e7d

Boyd, E., Chaffin, B. C., Dorkenoo, K., Jackson, G., Harrington, L., N'Guetta, A., Johansson, E. L., Nordlander, L., Paolo De Rosa, S., Raju, E., Scown, M., Soo, J., & **Stuart-Smith, R.F.** (2021). Loss and damage from climate change: A new climate justice agenda. *One Earth*, 4(10), 1365–1370. doi: 10.1016/j.oneear.2021.09.015.

Ebi, K. L., Åström, C., Boyer, C. J., Harrington, L. J., Hess, J. J., Honda, Y., Kazura, E., **Stuart-Smith, R. F.**, & Otto, F. E. L. (2020). Using Detection And Attribution To Quantify How Climate Change Is Affecting Health. *Health Affairs*, *39*(12), 2168–2174. doi: 10.1377/hlthaff.2020.01004.

Book chapters

Stuart-Smith, R.F., Otto, F.E.L., & Wetzer, T. (2022). Corporate liability for climate change impacts: the role of climate science. In: *Corporate Responsibility and Liability in relation to Climate Change* [de Jong, E.R., Kuipers, A., Roorda, L., Schaap, A.J., & Overheul, M. (eds.)]

In preparation / forthcoming

Steiner, J.F., et al. (forthcoming). Cryosphere and water-related disasters (observed and future changes). In: *The HKH Outlook Report: Cryosphere, Climate Change, Water, Ecosystems and Society.*

Wetzer, T., **Stuart-Smith, R.F.,** & Dibley, A. (in prep.). Climate risk assessments require engagement with the law.

Stuart-Smith, R.F., Rajamani, L., Rogelj, J., Wetzer, T. (in prep.). Appropriate use of carbon dioxide removal.

Stuart-Smith, R.F., Otto, F.E.L., Wetzer, T., et al. (in prep.). The climate harms of individual greenhouse gas emitters.

Stuart-Smith, R.F., Roe, G.H., Li, S. et al. (in prep.). Attribution of extreme glacier melt events to climate change.

Saad, A., **Stuart-Smith, R.F.**, & Wetzer, T. (in prep.). Causation and climate science in U.S. climate litigation.

Bonell, A., **Stuart-Smith, R.F.**, Li, S., Haines, A., et al. (in prep.). Attributing climate change impacts on foetal and maternal health in the Gambia.

Boyd, E., Otto, F.E.L., Lauta, K.C., Raju, E., James, R., **Stuart-Smith, R.F.**, Harrington, L.J., De Rosa, S.P., Soo, J., Jones, R.G. (in review). Attribution science, climate litigation and mobilisation around climate change – unexplored synergies for social transformations.

Nordlander, L., et al. (in review). Does climate change change everything? Science, Mobilisation and Policy in Sweden's responses to climate change-related disasters.

Boyd, E., Otto, F.E.L., De Rosa, S.P., **Stuart-Smith, R.F.**, Harrington, L.J., Soo, J. (in prep.). Socialising attribution of extreme events: progress, myths and challenges.

Reports

Li, S. & **Stuart-Smith, R.F.** (2022). The impacts of climate change in Brazil, and Brazil's contribution to global warming. Expert report for the Institute of Amazonian Studies.

Stuart-Smith, R.F. & Li, S. (2022). Greenhouse gas emissions from deforestation in Brazil, and the need for forest restoration. Expert report for the Institute of Amazonian Studies.

Stuart-Smith, R.F., Clarke, B.J., Harrington, L.H., Otto, F.E.L. (2021). Global Climate Change Impacts Attributable to Deforestation driven by the Bolsonaro Administration: Expert report for submission to the International Criminal Court.

Stuart-Smith, R.F., Saad, A., Otto, F.E.L., Lisi, G., Lauta, K.C., Minnerop, P. and Wetzer, T. (2021) Attribution science and litigation: facilitating effective legal arguments and strategies to manage climate change damages. Smith School of Enterprise and the Environment, Oxford.

Wilson, R., Ganti, G., Geiges, A., Gidden, M., **Stuart-Smith, R.F.**, Menke, I. (2020). Italy's Climate Targets and Policies in Relation to the Paris Agreement and Global Equity Considerations. Climate Analytics, Berlin.

Stuart-Smith, R.F. (2020). Climate change in the Arctic: impacts and attribution. Scoping study for WWF-UK.

Stuart-Smith, R.F., Roe, G.H., Li, S., & Allen, M.R. (2019). Human influence on the retreat of Palcaraju glacier (Cordillera Blanca, Peru). American Geophysical Union Fall Meeting.

8.2 Supplementary materials to Paper 1

Standards of proof in law.

Jurisdictions differ with respect to the tests used for evaluating causal claims, and in the required standard of proof, but climate litigants confront common difficulties when meeting the varying thresholds for establishing causation found in different jurisdictions. The U.S., England, Ireland, Denmark, and Lithuania adopt a "more probable than not" standard, whereas Austria and the Netherlands adopt a "high probability" and "reasonable degree of certainty" standard, respectively. In Germany a near certainty standard may be applied, but often judges simply need to be convinced of the existence of a causal link. Other continental European jurisdictions may adopt higher standards of proof: in Bulgaria and Spain certainty is expected, in Greece, France, Poland, and Italy a judge must be convinced that the causal link exists[76]. While the standard of proof is formulated differently across jurisdictions, it may be difficult to ascertain where it is, in practice, more or less stringent.

Previous research has argued that causation in law assesses the factors which act to produce an event. Specifically, the factors considered to be a cause of an event must have, at minimum, increased the *probability* of the event's occurrence in a statistically significant way[22]. While there are no established normative correctives in climate litigation, a coherent causal analysis requires re-thinking the fundamental normative assumptions (which would then also capture the existing exemptions from the 'but for' test). Previous scholarship has sought to address the lack of agreement on normative correctives in climate litigation by arguing that causal explanations for climate change impacts can be developed through demonstrating greenhouse gas emissions to be a necessary, sufficient, or sustaining (i.e., maintaining an effect) cause[22.] This would allow for a coherent causal analysis even in cases where the judiciary takes recourse to normative considerations to avoid placing the financial burden on those who have suffered the injury.

Causation tests used in climate litigation.

Scientific evidence is evaluated by the courts through the application of causation tests. Here, we outline the tests applied in cases where courts have considered questions of causation, and we identify the implications of such causation tests for the acceptance of climate change attribution evidence by the courts. In the cases analysed, courts applied various thresholds and tests for liability when adjudicating climate cases, depending on the cause of action and the stage that the litigation has reached.

Some courts adopted a low threshold for liability, finding that defendant's mere contribution to greenhouse gas emissions was sufficient to support a finding for liability. Other courts have required that a defendant's actions constituted material contributions to impacts in order to

be found liable for the alleged harms. Courts also adopt various tests when evaluating the linkage between defendants' emissions and plaintiffs' alleged harms. These tests underline the importance of causation to a claim for liability.

Causation tests used in US climate litigation.

In the U.S., courts have primarily had recourse to the 'but for' and 'fair traceability' tests.

Seven of the cases analysed applied the fair traceability test[115–117,232–235]. This test is used to establish standing under Article III of the US Constitution, and, following *Lujan v. Defenders of Wildlife*, requires that plaintiffs (1) prove an injury in fact, (2) establish causation, and (3) demonstrate the likelihood that the injury will be redressed by a favourable decision[236]. To satisfy the causation requirement, the alleged injury must be 'fairly traceable to the actions of the defendant'. This requires that there is a genuine nexus between a plaintiff's injury and a defendant's alleged conduct and ensures that the injury complained of is not the result of the actions of other parties who are not before the court.

The 'but for' test was applied in refs. [120–122,237], where the courts assessed the causal link between the cause of action and defendants' operations on the Outer Continental Shelf (OCS). This was necessary to establish federal jurisdiction under the Outer Continental Shelf Lands Act (OCSLA) and to remove the case from the state court to federal court. The test was applied narrowly, following the interpretation of *Deepwater Horizon*, according to which a case cannot be removed under OCSLA based on speculative impacts and an immediate and physical impact is needed.

The 'but for' test was also applied in ref. [113], in relation to fossil fuel production in California, to establish whether the court could exercise jurisdiction over a non-resident defendant. Following *Doe v American National Red Cross*, the required causal link would have been met if the plaintiff's injury would not have occurred "but for" the contacts between the defendant and the forum state. The plaintiffs therefore needed to establish that the harm alleged – namely the effects of global warming induced sea level rise – would not have occurred absent each defendant's respective California-related activities.

While the fair traceability and but-for tests appear most relevant in the cases, there were also some instances of US courts applying different causation tests. In a takings claim, St. Bernard Parish Government v United States (ref. [238]), the test used in ref. [239] was applied to determine whether an invasion was "the direct, natural and probable result" of an authorised activity, rather than merely an incidental or consequential injury that might be compensable as a tort.

Causation tests used in non-US climate litigation.

In non-US jurisdictions, courts have applied a range of causation tests in climate lawsuits due to the different causes of action involved.

In *Future Generations* (Colombia)[240], the causation test applied required that the injury to the fundamental rights with which the case was concerned must be the *immediate and direct consequence* of the disturbance to the collective right in order to establish standing to bring a collective action before the court. A test of similar stringency was carried out in the New Zealand courts' assessment of causation in *Smith v Fonterra*[118], which required damage to be 'particular, direct and substantial' and not 'a mere consequential injury', if causation is to be established. This test exists under the doctrine of public nuisance and is similar to the causation test applied in *St. Bernard Parish Government* (Claims Court) and *St. Bernard Parish Government* (Court of Appeals).

In *Lliuya* (Germany)[241] the District Court of Essen applied the conditio sine qua non test combined with the principle of adequate causation, following the Federal Court of Justice in NJW 1990, 2882 and the Higher District Court of Düsseldorf in NJW 1998, 3720. This test is applied for any claim of reparations for the expenditures made toward the removal of the impairment from the disturber (i.e., compensation for liable losses) under §1004 of the German Civil Code. According to this test, a causal link is established if the action or inaction, had it not occurred, would result in the damage being undone. In cases where harm results from multiple actions by different actors, as is the case with climate change impacts, establishing causation would require showing that the harm would have been avoided had the defendant's actions not occurred. What makes this test a steep hurdle to establishing causation is the principle of adequacy, according to which the defendants' actions or inactions must have substantially increased the likelihood of an effect of the same sort as the one that occurred. This restricts the 'condition sine qua non' test and prevents improbable causal processes from triggering liability.

Finally, in *Urgenda* (the Netherlands)[242] the Hague Court of Appeals applied the 'real risk of the danger for which measures have to be taken' test, while the UN Human Rights Committee's Views Adopted on *Teitiota Communication*[243] applied a 'real risk of irreparable harm' test.

Approaches to conducting attribution studies.

Climate change attribution studies typically assess how the statistics of an extreme event or slow-onset change differs in the present climate, as compared with a counterfactual climate without anthropogenic greenhouse gas and aerosol emissions. Studies can also exclude subsets of these emissions, to quantify the change attributable to individual companies or countries[30,32,80,81]. The findings of all types of studies are sensitive to how the climate change impact evaluated is defined.

The definition of a climate change impact in attribution studies is usually designed to best assess the impacts experienced, within the constraints of available meteorological data and

the need to focus on meteorological variables which climate models can simulate with greatest confidence[106]. For instance, studies interested in the impacts of heatwaves on human health have considered maximum 3-day wet-bulb temperature as a metric which is a useful proxy for heat stress on the human body[244]. Protocols are available for supporting the choice of spatial area and timescale evaluated in the event definition[46], but contrasting event definitions can still be chosen and influence the findings of attribution studies.

In our manuscript, the descriptions of attribution science focus primarily on the methods used for evaluating the role of human influence on extreme climate-related events described in Stott et al.[74]. These methods are the most commonly used in attribution studies conducted to date, and following from the approach proposed by Allen[226], were developed with explicit reference to evaluating the questions of relevance in climate litigation: if not for the influence of climate change, how would the impacts on plaintiffs have differed?

Another branch of attribution science has also been developed, known as the 'Boulder' approach[245]. This method asks the question: given a certain set of atmospheric conditions that led to an extreme event, how did climate change alter its impacts[246]? This approach evaluates how climate change influences processes such as changing sea-surface temperatures which contribute to moisture availability for a storm. However, it does not necessarily quantify the influence of these causal factors on the overall probability of an event's occurrence. Consequently, these methods do not fit as well with the legal framing of causal analysis.

Country	Cause of action	Case name	Summary	Case Outcome (as of November 2020)	Key case documents used in analysis
AUSTRALIA	Judicial review	*Bushfire Survivors for Climate Action Incorporated v New South Wales Environment Protection Authority*	Action seeking to compel regulation of greenhouse gas emissions in response to the harm caused by bush fires made likely and more intense by climate change.	Pending	Summons, Reply
AUSTRALIA	Judicial review	*Nucifora v Valuer-General*	Challenge to a land valuation for not taking into account the impacts of climate change.	Dismissed	Decision
AUSTRALIA	Human rights	*Youth Verdict v Waratah Coal*	Challenge to a proposed coal mine on the basis that by contributing to climate change the mine would infringe on human rights.	Pending	Objection
BELGIUM	Human rights	*VZW Klimaatzaak v Kingdom of Belgium & Others*	Action seeking to compel Belgian federal and regional governments to reduce greenhouse gas emissions more aggressively.	Pending	Summons
CANADA	Human rights	*ENVironnement JEUnesse v Canada*	Class action seeking declaratory relief, order for cessation and punitive damages for human rights violations of citizens aged 35 and under resulting from Canada's failure to set greenhouse gas emission reduction target and plan to avoid dangerous climate change impacts.	Pending	Application, Judgment
CANADA	Human rights	*Lho'imggin et al. v Her Majesty the Queen*	Action seeking declaratory relief for human rights violations resulting from Canada's greenhouse gas emission reduction targets and approval of GHG-emitting projects.	Pending	Complaint
CANADA	Judicial review	*Mathur, et al. v Her Majesty the Queen in Right of Ontario*	Challenge to the Ontario's 2030 greenhouse gas reduction target for infringing on human rights of current and future generations of Ontarians.	Pending	Complaint, Notice of Motion to Dismiss
COLOMBIA	Human rights	*Future Generations v Ministry of the Environment and Others*	Action seeking to enforce fundamental right to a healthy environment which is threatened by climate change and government's failure to reduce deforestation.	Successful	Amicus Brief, Decision (Lower Court), Decision (Supreme Court)
GERMANY	Human rights	*Family Farmers and Greenpeace Germany v Germany*	Action seeking compensatory damages for human rights violations resulting from the government's insufficient action to meet its 2020 GHG emissions reduction target.	Dismissed	Complaint, Judgment
GERMANY	Tort	*Lliuya v RWE*	Action seeking to hold Germany's largest electricity producer liable for harms arising in different jurisdictions resulting from the warming effects of climate change.	Pending	Complaint, Reply, Grounds of Appeal, Decision (District Court of Essen), Order (Regional Court of Hamm)
Inter-American Commission on Human Rights	Human rights	*Petition to the Inter-American Commission on Human Rights Seeking Relief from Violations of the Rights of Arctic Athabaskan Peoples Resulting from Rapid Arctic Warming and Melting Caused by Emissions of Black Carbon by Canada*	Petition to the Commission seeking relief for human rights violations resulting from Canada's failure to regulate the black carbon emissions on the basis that it threatens the Athabaskan people's human rights by contributing to arctic warming.	Pending	Petition
Inter-American Commission on Human Rights	Human rights	*Petition to the Inter-American Commission on Human Rights Seeking Relief From Violations Resulting from Global Warming Caused By Acts and Omissions of the United States*	Petition to the Commission seeking relief from human rights violations resulting from global warming caused by acts and omissions of the United States.	Dismissed	Petition, Testimony, Testimony, Decision
IRELAND	Judicial review / human rights	*Friends of the Irish Environment v Ireland*	Challenge to the Irish government's approval of the National Mitigation Plan for violating statutory law, the Irish Constitution, and human rights obligations because it was not set to reduce GHG emissions sufficiently over the near-term.	Successful	Judgment (High Court), Judgment (Supreme Court)
NETHERLANDS	Tort / human rights	*Milieudefensie et al. v Royal Dutch Shell plc.*	Action seeking to hold private company liable for violation of duty of care and human rights obligations by failing to take adequate action to curb its contributions to climate change.	Pending	Summons
NETHERLANDS	Tort / human rights	*Urgenda Foundation v State of the Netherlands*	Action seeking declaratory judgment and an injunction to compel the Dutch government to reduce GHG emissions.	Successful	Summons, Respondent's Notice on Appeal and Notice of Cross-

Country	Cause of action	Case name	Summary	Case Outcome (as of November 2020)	Key case documents used in analysis
					Appeal, Decision (District Court), Decision (Hague Court of Appeal), Decision (Supreme Court)
NEW ZEALAND	Human rights	*AD (Tuvalu)*	Action from Tuvalu family seeking resident visa in New Zealand on the basis that they would be at risk of suffering the adverse impacts of climate change if they were deported to Tuvalu.	Successful	Decision
NEW ZEALAND	Human rights	*Ioane Teitiota v The Chief Executive of the Ministry of Business, Innovation and Employment*	Action from Kiribati citizen seeking refugee status in New Zealand on the basis that they would be at risk of suffering the adverse impacts climate change on Kirabati, namely rising ocean levels and environmental degradation.	Dismissed	Judgment (High Court), Judgment (Supreme Court)
NEW ZEALAND	Judicial review	*Mataatua District Maori Council v New Zealand*	Action seeking declaratory relief for New Zealand's failure to meet its obligations to the Maori by failing to implement policies that will address climate change.	Pending	Application
NEW ZEALAND	Public nuisance / negligence / tort	*Smith v Fronterra Co-Operative Group Ltd and Ors*	Action seeking to hold major GHG emitters liable for harms arising from their polluting activities that allegedly constitute public nuisance, negligence and breach of a duty cognizable at law to cease contributing to climate change.	Dismissed	Judgment
PAKISTAN	Human rights / public trust	*Ali v Fedaration of Pakistan*	Petition seeking injunctive relief for human rights violations resulting from various actions and inactions of the government, in particular seeking an injunction against the development of coal fields in the Thar region.	Pending	Petition
PAKISTAN	Human rights	*Leghari v Federation of Pakistan*	Action challenging the government's failure to carry out national climate change policy and targets for violation of human rights.	Successful	Order, Supplemental Order, Judgment
PHILIPPINES	Human rights	*In re Greenpeace Southeast Asia and Others*	Petition seeking investigation into the allegation that major fossil fuel companies violated human rights by causing climate change and ocean acidification.	Pending	Petition, Exhibit L - Literature review, Documentary evidence, Responses and comments on the Petition from interested parties, Press release from the Philippines Commission on Human Rights, Press release from the Philippines Commission on Human Rights
SOUTH KOREA	Human rights	*Kim Yujin et al. v South Korea*	Action challenging the government's insufficient action under climate change law for violation of fundamental rights.	Pending	Complaint, Supplemental Complaint
SWITZERLAND	Human rights	*Union of Swiss Senior Women for Climate Protection v Swiss Federal Council and Others*	Action challenging the adequacy of the Swiss government's climate change mitigation targets and implementation measures for violating human rights and particularly affecting demographic groups vulnerable to heat waves.	Dismissed	Petition, Judgment (Federal Administrative Court), Appeal, Judgment (Federal Supreme Court)
UGANDA	Public trust	*Mbabazi and Others v The Attorney General and National Environmental Management Authority*	Action seeking declaratory and injunctive relief on behalf of four Ugandan minors for the government's failure to meet its obligations to mitigate climate change pursuant to the public trust doctrine.	Pending	Complaint, Amended Complaint
United Nations Committee on the Rights of the Child	Human rights	*Sacchi et al. v Argentina et al.*	Petition alleging that Argentina, Brazil, France, Germany and Turkey violated children's rights under international law by making insufficient cuts to greenhouse gases and failing to use available tools to protect children from carbon pollution.	Pending	Petition, Appendix (part 1), Appendix (part 2), Petitioners' Reply to Admissibility Objections
United Nations	Human rights	*UN Human Rights Committee Views Adopted on Teitiota Communication*	Communication to the UN Human Rights Committee alleging that New Zealand violated human rights through the denial of refugee status	Dismissed	Opinion

Country	Cause of action	Case name	Summary	Case Outcome (as of November 2020)	Key case documents used in analysis
Human Rights Committee			to Kiribati citizen despite assertions that climate change made Kiribati unhabitable.		
United Nations Special Rapporteurs	Human rights	*Rights of Indigenous People in Addressing Climate-Forced Displacement*	Human rights-complaint to the United Nations Special Rapporteurs alleging that the U.S. government failed to address climate-caused displacement.	Pending	Complaint
USA	Public nuisance	*American Electric Power Co. v Connecticut*	Public nuisance lawsuit seeking imposition of caps and reduction of greenhouse gas emissions from power companies.	Dismissed	Complaint, Opinion and Order (U.S. District Court), Opinion (U.S. Court of Appeals), Opinion (U.S. Supreme Court)
USA	Public trust	*Aronow v Minnesota*	Challenge under the public trust doctrine against Minnesota's failure to regulate greenhouse gas emissions.	Dismissed	Complaint, Order granting motion to dismiss (Ramsey County District Court), Opinion (Court of Appeals of the State of Minnesota)
USA	Public trust	*Blades v California*	Action seeking declaration that atmosphere is a public trust resource that the State of California has an obligation to protect for its current and future citizens, including by imposing greenhouse gas restrictions	Dismissed	Complaint
USA	Public nuisance	*Board of County Commissioners of Boulder County v Suncor Energy (U.S.A.), Inc.*	Action seeking damages and other relief from fossil fuel companies for climate change harms.	Pending	Complaint, Amended complaint, Order granting motion to remand (U.S. District Court), Order to file response to amici curiae brief (U.S. Court of Appeals), Opinion (U.S. Court of Appeals)
USA	Public nuisance	*California v General Motors Corp.*	Public nuisance action by California seeking damages from car companies for their contributions to climate change.	Dismissed	Complaint, Defendants' Motion to dismiss, Order granting motion to dismiss (U.S. District Court)
USA	Public trust	*Center for Environmental Law & Policy v State of Washington*	Challenge to government's failure to protect Spokane River flows which petitioners alleged was experiencing a low flow trend due to climate change and other factors.	Dismissed	Petition, Response, Order on petition (Thurston County Superior Court), Opinion and order (Court of Appeals of the State of Washington)
USA	Public nuisance / negligence / trespass	*City & County of Honolulu v Sunoco LP*	Action seeking damages and other relief from fossil fuel companies for actually and proximately causing climate change impacts.	Pending	Complaint, Order lifting litigation stay (U.S. District Court)
USA	Public nuisance / negligence / trespass	*City of Charleston v Brabham Oil Company*	Action seeking to hold fossil fuel companies liable for the impacts of climate change resulting from the failure to warn of threats posed by fossil fuel products, wrongful promotion, public deception campaigns and failure to pursue less hazardous alternatives.	Pending	Complaint
USA	Public nuisance / negligence / trespass	*City of Hoboken v Exxon Mobil Corp. et al*	Action seeking compensation and injunctive relief for climate change-related injuries allegedly resulting from the energy companies' production of fossil fuels and concealment of fossil fuels' harms.	Pending	Complaint
USA	Public nuisance / negligence / tort / trespass	*City of Imperial Beach v Chevron Corp.*	Action seeking damages and other relief from fossil fuel companies for injuries caused by sea level rise.	Pending	Complaint, Amicus brief
USA	Public nuisance / trespass	*City of New York v BP p.l.c.*	Action seeking to hold fossil fuel companies liable for city's climate change-related injuries.	Pending	Complaint, Amended complaint, Memorandum of law (Chevron, ConocoPhillips, Exxon Mobil), Opposition to ConocoPhillips'

Country	Cause of action	Case name	Summary	Case Outcome (as of November 2020)	Key case documents used in analysis
					Motion to Dismiss, Brief filed by defendants-appellees (Chevron Corporation, Exxon Mobil Corporation, and ConocoPhillips), Opinion and Order granting motion to dismiss (U.S. District Court)
USA	Public nuisance	*City of Oakland v BP p.l.c.*	Action seeking to hold fossil fuel companies liable for city's climate change-related injuries.	Pending	Complaint, Defendants' Amici Curiae Briefs, Response of Amici to request for information re amicus curiae materials, Defendants' Motion to dismiss, Order denying motions to remand (U.S. District Court), Request for information re amicus curiae materials (U.S. District Court), Notice re Tutorial and some questions for the tutorial (U.S. District Court), Request for Supplemental Briefing (U.S. District Court), Notice re Briefing on motion to dismiss (U.S. District Court), Order granting motion to dismiss amended complaints (U.S. District Court), Order granting motions to dismiss for lack of personal jurisdiction (U.S. District Court) Opinion (U.S. Court of Appeals), Order and amended opinion (U.S. Court of Appeals)
USA	Public nuisance / negligence / trespass	*City of Richmond v Chevron Corp.*	Action seeking to hold fossil fuel companies liable for city's climate change-related injuries.	Pending	Complaint, Order granting motions to remand (U.S. District Court), Order (U.S. Court of Appeals)
USA	Public nuisance / negligence / trespass	*City of Santa Cruz v Chevron Corp.*	Action seeking to hold fossil fuel companies liable for city's climate change-related injuries.	Pending	Complaint, Order granting motions to remand (U.S. District Court), Order (U.S. Court of Appeals)
USA	Judicial review	*Coalition for Responsible Regulation v Environmental Protection Agency*	Challenge to EPA's greenhouse gas regulations declaring that greenhouse gas emissions endanger public health and welfare.	Dismissed	Petition for a writ of certiorari
USA	Public nuisance / negligence / tort / trespass	*Comer v Murphy Oil USA, Inc (1)*	Action seeking to hold energy and other companies liable for damages related to Hurricane Katrina.	Dismissed	Complaint, Opposition
USA	Public nuisance / negligence / tort / trespass	*Comer v Murphy Oil USA, Inc (2)*	Action seeking to hold energy and other companies liable for damages related to Hurricane Katrina.	Dismissed	Complaint, Memorandum opinion and order granting defendants' motion to dismiss (U.S. District Court), Opinion (U.S. Court of Appeals)

Country	Cause of action	Case name	Summary	Case Outcome (as of November 2020)	Key case documents used in analysis
USA	Judicial review	*Conservation Law Foundation v EPA*	Challenge to the Trump administration's amendments to the Clean Water Act's definition of "waters of the United States".	Dismissed	Complaint
USA	Public nuisance / negligence / tort / trespass	*County of Marin v Chevron Corp.*	Action seeking to hold fossil fuel companies liable for county's climate change-related injuries.	Pending	Complaint
USA	Public nuisance / negligence / tort / trespass	*County of San Mateo v Chevron Corp.*	Action seeking to hold fossil fuel companies liable for county's climate change-related injuries.	Pending	Complaint, Amici Curiae Briefs, Order granting motions to remand (U.S. District Court), Order granting motions to stay (U.S. District Court), Opinion (U.S. Court of Appeals)
USA	Public nuisance / negligence / trespass	*County of Santa Cruz v Chevron Corp.*	Action seeking to hold fossil fuel companies liable for city's climate change-related injuries.	Pending	Complaint, Order granting motions to remand (U.S. District Court), Order (U.S. Court of Appeals)
USA	Public nuisance / negligence / trespass	*Delaware v BP America Inc.*	Action seeking to hold the fossil fuel industry liable for the physical, environmental, social, and economic impacts of climate change resulting from the concealment and misrepresentation of their products' known dangers and simultaneous promotion of their unrestrained use.	Pending	Complaint
USA	Trespass / defamation	*Energy Transfer LP v Greenpeace International*	Action seeking to hold Greenpeace and other organisations liable for raising money based on false information about Dakota Action Pipeline's environmental impact and providing funds to support protestors.	Dismissed	Complaint
USA	Takings	*Harris County Flood Control District v Kerr*	Action seeking to hold municipal entity liable under a takings theory for flood damage resulting from global warming.	Dismissed	Petitioners' Reply Brief on the merits, Respondents' brief on the merits, Opinion (Supreme Court of Texas)
USA	Public trust	*Held v State of Montana*	Action seeking declaration of right to a stable climate system and order to compel Montana to prepare and implement a remedial plan to reduce GHG emissions.	Pending	Complaint
USA	Federal statutory claim	*High Country Conservation Advocates v United States Forest Service (2013)*	Challenge to the federal approvals of an underground coal mine expansion for failure to adequately consider greenhouse gas impacts.	Successful	Complaint, Order (U.S. District Court), Order (U.S. District Court)
USA	Federal statutory claim	*High Country Conservation Advocates v U.S. Forest Service (2017)*	Challenge to the federal approvals of an underground coal mine expansion for failure to adequately consider greenhouse gas impacts in new supplemental environmental impact reviews conducted by the federal government.	Pending	Complaint, Opposition, Order (U.S. District Court), Order granting Emergency Motion for Injunction (U.S. Court of Appeals)
USA	Takings	*Illinois Farmers Insurance Co. v Metropolitan Water Reclamation District of Greater Chicago*	Class action brought by insurance companies seeking damages for increased pay-outs to the plaintiffs' insureds who suffered flooding as a result of municipalities' failure to implement adequate stormwater management plans.	Dismissed	Complaint, Notice of Dismissal
USA	Public trust / constitutional rights	*Juliana v United States*	Action by young plaintiffs alleging that the federal government violated their constitutional rights by causing dangerous concentrations of fossil fuel carbon emissions.	Dismissed	Amended complaint, Expert Reports, Opinion (U.S. Court of Appeals)
USA	Public nuisance / trespass	*King County v BP p.l.c.*	Public nuisance and trespass action against fossil fuel companies seeking funding of climate change adaptation program.	Pending	Complaint, Order granting stay (U.S. District Court)

Country	Cause of action	Case name	Summary	Case Outcome (as of November 2020)	Key case documents used in analysis
USA	Public trust / constitutional rights	*Komor v United States*	Constitutional climate change action seeking an order requiring the federal government to research and establish a program for direct atmospheric carbon removal.	Pending	Complaint, Order granting motion for stay (U.S. District Court)
USA	Public nuisance	*Korsinsky v EPA*	Action seeking to hold federal and New York state and local environmental agencies liable for climate change.	Dismissed	Petition for a writ of certiorari, Memorandum decision (U.S. District Court), Summary Order (U.S. Court of Appeals)
USA	Public nuisance / negligence / trespass	*Mayor and City Council of Baltimore v BP p.l.c.*	Action seeking to hold fossil fuel companies liable for climate change impacts.	Pending	Complaint, Memorandum opinion (U.S. District Court), Order (U.S. Court of Appeals)
USA	Public nuisance	*Native Village of Kivalina v ExxonMobil Corp.*	Action seeking to hold oil and power companies liable for impacts of climate change caused by sea rising.	Dismissed	Complaint, Notice of Motion to dismiss, Order granting defendants' motions to dismiss (U.S. District Court), Opinion (U.S. Court of Appeals)
USA	Public nuisance / negligence	*Pacific Coast Federation of Fishermen's Associations, Inc. v Chevron Corp.*	Action by a commercial fishing industry trade group seeking to hold fossil fuel companies liable for adverse climate change impacts to the ocean off the coasts of California and Oregon that resulted in prolonged closure of Dungeness crab fisheries.	Pending	Complaint, Joint stipulation to stay proceedings
USA	Public nuisance	*People of State of California v BP p.l.c. (San Francisco)*	Action seeking to hold fossil fuel companies liable for city's climate change-related injuries.	Pending	Complaint
USA	Negligence	*Pietrangelo v S & E Customize It Auto Corp.*	Action seeking compensation for damage incurred to the vehicle stored at repair shop during Hurricane Sandy that was prevented from defendant's negligent failure to have flood insurance.	Dismissed	Opinion and Order (Richmond County Civil Court)
USA	Public trust	*Reynolds v Florida*	Action alleging government's violation of fundamental right to a stable climate system and seeking to compel government to take climate action.	Dismissed	Complaint, Order granting motion to dismiss with prejudice (Leon County Circuit Court)
USA	Public trust / nuisance / negligence / trespass	*Rhode Island v Chevron Corp.*	Action seeking to hold fossil fuel companies liable for causing climate change impacts that adversely affected Rhode Island and jeopardised state-owned and state-operated facilities, real property, and other assets.	Pending	Complaint, Motions to Dismiss, Opposition to motions to dismiss, Opinion and Order (U.S. District Court), Order (U.S. Court of Appeals)
USA	Public trust	*Sinnok v Alaska*	Action seeking injunctive and declaratory relief for violation of youth plaintiff's rights to a stable climate system resulting from Alaska's climate and energy policies.	Dismissed	Complaint, Order granting state's motion to dismiss (Superior Court for the State of Alaska)
USA	Takings	*St. Bernard Parish Government v United States*	Action seeking compensation for temporary taking of property caused by flooding during Hurricane Katrina and other hurricanes resulting from government's inaction, including the failure to properly maintain or modify the Mississippi River-Gulf Outlet.	Dismissed	Memorandum Opinion and Order (U.S. Court of Federal Claims), Opinion (U.S. Court of Appeals)
USA	Contract	*Steadfast Insurance Co. v The AES Corp.*	Action by insurance company seeking declaratory judgment that it was not obligated to defend or indemnify its policyholder in underlying litigation seeking climate change-related damages.	Successful	Complaint, Order (Arlington County Circuit Court), Opinion (Supreme Court of Virginia), Opinion (Supreme Court of Virginia)
USA	Public trust	*Svitak v Washington*	Action seeking declaration that the State of Washington had the obligation to protect atmosphere as public trust and to accelerate its greenhouse gas reductions.	Dismissed	Complaint, State's response brief, Order (King County Superior Court), Opinion (Court of Appeals of the State of Washington)

Country	Cause of action	Case name	Summary	Case Outcome (as of November 2020)	Key case documents used in analysis
USA	Takings / public nuisance / negligence / trespass	*Tzakis v Berger Excavating Contractors, Inc.*	Action seeking to hold municipal defendants liable for failure to prepare for climate change impacts that allegedly contributed to property damage during floods in 2008.	Dismissed	Complaint, Order (Cook County Circuit Court)
USA	Federal statutory claim	*WildEarth Guardians v Bernhardt*	Challenge to the federal approval of a mining plan for the expansion of a coal mine in Colorado based on the need for further analysis regarding a methane flaring alternative and potential impacts to perennial streams.	Successful	Petition, Order (U.S. District Court)

Supplementary Table 1: List of cases analysed within the project scope, the jurisdiction in which the case was brought, cause of action, brief case summary, outcome as of November 2020, and key documents used from each case to inform our findings.

Case name	Meteorological impacts	Sea-level rise	Glacial retreat
Bushfire Survivors for Climate Action Incorporated v New South Wales Environment Protection Authority	X	X	
Youth Verdict v Waratah Coal	X	X	
VZW Klimaatzaak v Kingdom of Belgium & Others	X		
ENVironnement JEUnesse v Canada	X		
Lho'imggin et al. v Her Majesty the Queen	X		
Mathur, et al. v Her Majesty the Queen in Right of Ontario	X		
Family Farmers and Greenpeace Germany v Germany	X		
Lliuya v RWE			X
Petition to the Inter-American Commission on Human Rights Seeking Relief from Violations of the Rights of Arctic Athabaskan Peoples Resulting from Rapid Arctic Warming and Melting Caused by Emissions of Black Carbon by Canada	X		
Petition to the Inter-American Commission on Human Rights Seeking Relief From Violations Resulting from Global Warming Caused By Acts and Omissions of the United States	X		
Milieudefensie et al. v Royal Dutch Shell plc.	X	X	
Urgenda Foundation v State of the Netherlands	X	X	
AD (Tuvalu)	X	X	
Mataatua District Maori Council v New Zealand	X	X	
Smith v. Fonterra Co-Operative Group Ltd and Ors	X	X	
Ali v Fedaration of Pakistan	X		
In re Greenpeace Southeast Asia and Others	X	X	
Kim Yujin et al. v South Korea	X		
Union of Swiss Senior Women for Climate Protection v Swiss Federal Council and Others	X		X
Mbabazi and Others v The Attorney General and National Environmental Management Authority	X		
Sacchi et al. v Argentina et al.	X	X	
Rights of Indigenous People in Addressing Climate-Forced Displacement	X	X	

Case name	Meteorological impacts	Sea-level rise	Glacial retreat
American Electric Power Co. v Connecticut	X	X	
Aronow v Minnesota	X		
Blades v California	X	X	X
Board of County Commissioners of Boulder County v Suncor Energy (U.S.A.), Inc.	X		
California v General Motors Corp.	X	X	X
Center for Environmental Law & Policy v State of Washington	X		
City & County of Honolulu v Sunoco LP	X	X	
City of Charleston v Brabham Oil Company	X	X	
City of Hoboken v Exxon Mobil Corp. et al	X	X	
City of Imperial Beach v Chevron Corp.		X	
City of New York v BP p.l.c.	X	X	
City of Oakland v BP p.l.c.		X	
City of Richmond v Chevron Corp.	X	X	
City of Santa Cruz v Chevron Corp.	X	X	
Comer v Murphy Oil USA, Inc (1)	X		
Comer v Murphy Oil USA, Inc (2)	X	X	
Conservation Law Foundation v EPA	X		
County of Marin v Chevron Corp.		X	
County of San Mateo v Chevron Corp.		X	
County of Santa Cruz v Chevron Corp.	X	X	
Delaware v BP America Inc.	X	X	
Harris County Flood Control District v Kerr	X		
Held v State of Montana	X		X
High Country Conservation Advocates v United States Forest Service	X		X
High Country Conservation Advocates v U.S. Forest Service	X		X
Illinois Farmers Insurance Co. v Metropolitan Water Reclamation District of Greater Chicago	X		

Case name	Meteorological impacts	Sea-level rise	Glacial retreat
Juliana v United States	X	X	X
King County v BP p.l.c.	X	X	X
Komor v United States	X	X	X
Mayor and City Council of Baltimore v BP p.l.c.	X	X	
Native Village of Kivalina v ExxonMobil Corp.		X	
Pacific Coast Federation of Fishermen's Associations, Inc. v Chevron Corp.	X		
People of State of California v BP p.l.c. (San Francisco)		X	
Reynolds v Florida	X	X	
Rhode Island v Chevron Corp.	X	X	
Sinnok v Alaska	X	X	X
Steadfast Insurance Co. v The AES Corp.	X	X	
Svitak v Washington	X	X	X
Tzakis v Berger Excavating Contractors, Inc.	X		

Supplementary Table 2: Climate change impacts driving losses alleged in analysed cases.

8.3 Supplementary materials to Paper 2

Increased outburst flood hazard from Lake Palcacocha due to human-induced glacier retreat

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Supplementary information

In this supplementary material to the paper "Increased outburst flood hazard from Lake Palcacocha due to human-induced glacier retreat" we explore the response of our flowline glacier model to uncertainty in the position of the glacier terminus in the 19th Century and provide further details about the conservative assumptions made in calculating the natural length variability of Palcaraju glacier for our statistical analysis.

Sensitivity of results to the location of the glacier terminus in the 19th Century

We estimate the position of the 19th Century terminus in the absence of direct observations as 4250m in horizontal distance along the glacier flowline, from the top of Palcaraju (see Methods). Based on geomorphological and lichenometric constraints on past glacier-length variability, the sensitivity of the glacier over the period for which there are length and temperature observations, and our modelling of the glacier's pre-1940 length change, it is unlikely that equilibrium position of the terminus lay far from this location.

In Fig. S1, we show that the flowline glacier model is insensitive to reasonable uncertainty in the equilibrium position of the 19th Century terminus (±200 m). We modulate the 19th Century terminus position at equilibrium by adjusting the ELA up and down. Due to the shallow slope of the base of the valley around the 19th Century terminus, only small changes in the ELA (±5m) are required for the 200m changes in glacier length. Since mountain glaciers have multidecadal response times[51,132], these small changes in ELA have little effect on the modelled present-day terminus position (shown to be approximately equal to that observed in Fig. 3 of the main text). Consequently, our flowline model remains consistent with observations despite uncertainty in the 19th Century terminus position.

Our statistical analysis of Palcaraju glacier's retreat from 1880 to present is insensitive to uncertainty in the 19th Century terminus position since the estimated retreat far exceeds the 3σ range of glacier length variability and even if the overall retreat were 1650m (rather than 1850m, as estimated in the main text), we would still conclude that it is virtually certain (>99% probability) that the observed retreat of Palcaraju glacier could not have occurred due to natural variability alone and therefore requires a climate change. The assumed 19th-Century terminus position appears to have more impact on the timing of the period of rapid retreat, but since this is also very sensitive to the imposed climate forcing (Fig. 2b, main text) we choose to use an independent best-estimate rather than adjusting the 19th-Century terminus position to fit the subsequent evolution of the glacier.

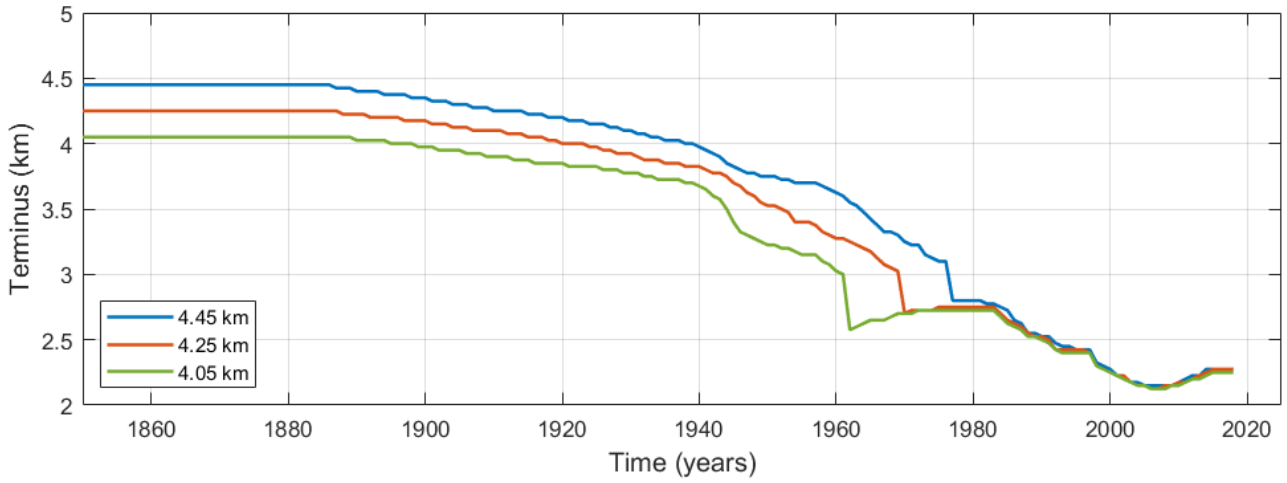


Figure S1: As Fig. 3b but with the 1850 glacier profile set in three equilibrium positions, at 4.05, 4.25 and 4.45 km along the flowline. Uncertainty in the mid-19th Century terminus position does not affect the present-day position of the glacier.

Assumptions in calculating the natural length variability of Palcaraju glacier

Our statistical analysis compares the estimated retreat of Palcaraju glacier with a PDF of the modelled natural length variability of the glacier in the absence of a temperature trend. The natural length variability is calculated according to Equation 4 (see Methods) as the product of the standard deviation of glacier length, the null signal-to-noise ratio of mass balance and an amplification factor which depends only on the duration of the temperature trend and the glacier response time (τ). In Fig. 4 of the main text, we show that we account for uncertainty in the duration of the response time with a PDF (grey shaded area on the horizontal axis).

Our calculations incorporate uncertainty in the glacier response and follow ref. [39], to which we refer a reader for details. Fig S2a shows the PDFs of the signal-to-noise ratios in mass balance that occur due to random variability in the absence of a climate trend, for 60-year and 140-year intervals. Fig. S2b shows the PDF of the signal-to-noise ratio of glacier length given only natural variability (i.e. no trend), for 60-year and 140-year intervals. Figure S2c shows the PDF for uncertainty in σ_L. Based on our numerical modelling, we chose a gamma function with a mean of 235 m, and 95% bounds of 115 to 345 m. Finally, in Fig. S2d,

combining the uncertainties from Figs S2b and S2c, we supplement Figs. 4e and 4f with the cumulative frequency of the modelled $\Delta L|_{null}$ and show that the estimated retreat from 1880 to 1940 and the present exceeds the 99th percentile of probable length change over these 60 and 140-year periods of temperature change.

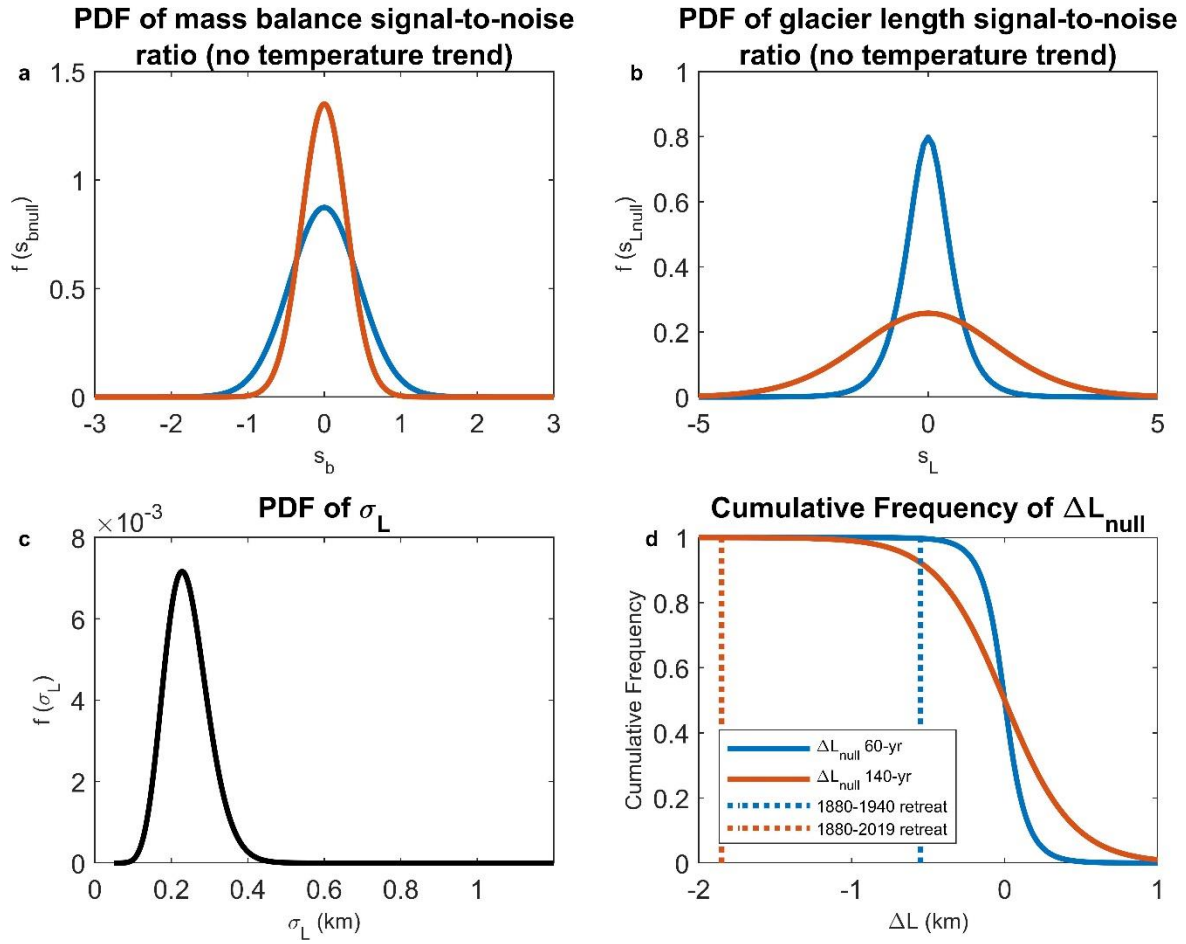


Figure S2. (a) PDF of the signal-to-noise ratio of Palcaraju glacier's mass balance over a 140-year (red) and 60-year (blue) period due to natural climate variability alone, in the absence of a temperature trend; (b) PDF of the signal-to-noise ratio of glacier length over a 140-year (red) and 60-year (blue) period due to natural climate variability alone, in the absence of a temperature trend; (c) PDF of the standard deviation of glacier length in the absence of a climate trend; and (d) the cumulative frequency of the probability of glacier length changes over a 140-year (red) and 60-year (blue) period, as compared with the estimated retreat of the glacier from 1880-2019 (red dashed line) and 1880-1940 (blue dashed line).

Sensitivity of our results to trends and variability in precipitation and temperature

Sensitivity of ELA to temperature. For a 1 K increase in temperature, our lapse rate yields a 180 m increase in the ELA (see Table S1). Using an energy balance model, ref. [112] also find a 180 m increase per +1 K for the northern outer tropics at this latitude. Ref. [157] gives a value of 182 m per +1 K.

Sensitivity of ELA to precipitation. For Palcaraju, a 10% increase in annual-mean precipitation raises mass balance by approximately 0.1 m yr^{-1} which, for our calculations, gives a 13 m decrease in ELA. We can normalise other results in the literature to the same perturbation. With an energy-balance model, ref. [112] finds a 16 m decrease in ELA for +0.1 m yr^{-1}. Using geometric profiles, ref. [157] estimates an 8 m decrease in ELA for +0.1 m yr^{-1}. Finally, from two years of observations on Shallap glacier, ref. [152] report a ~30 m

difference in ELA for a 35% difference in accumulation-area mass balance. These results all show smaller impacts on the ELA than a 1 K increase in temperature and are indicative of the greater importance of temperature than precipitation for changes in tropical mass balance.

The implications of these ELA sensitivities to temperature and precipitation. From 1880 to 2020, the observed long-term trend in temperature is 1.3 K. Long-term trends in local precipitation are for the most part, not statistically significant[156]. Theory and modelling suggests that, in general, average precipitation scales at about 1.5% per 1 K of temperature change[247]. In Table S1, we consider an extreme assumption of a 10% change in average precipitation over 1880 to 2020. From the above literature review and our own calculations, these results all support our contention that the temperature trends are far more important than plausible precipitation trends for the ELA and mass balance of this glacier.

Interannual variability. The standard deviation (σ) of annual-mean temperature in the HadCRUT4-CW dataset is $\sigma_T = 0.55$ K, and that of annual accumulation is $\sigma_P = 0.2$ m yr^{-1}, according to the Legates and Wilmot precipitation dataset[175]. Table S1 shows what these values imply for the standard deviations in ELA ($\sigma_{z_{ela}}$) and mass balance (σ_b), for both the preindustrial and modern glacier profiles. Results are similar for both profiles, so we discuss only the modern profiles here.

ELA. For temperature variability only, we find $\sigma_{z_{ela}}$= 100 m, for precipation variability only, $\sigma_{z_{ela}}$= 19 m. Combined variability is calculated as the square root of the sum of the squares, or $\sigma_{z_{ela}}$ = 102 m. Energy-balance-model estimates of these quantities indicate values of 85 m, 30 m, and 90 m, respectively[112]. Both sets of results reinforce the importance of temperature fluctuations in these settings.

Mass balance. For temperature variability only, we find σ_b = 0.8 m yr^{-1}. For precipitation variability only, σ_b = 0.2 m yr^{-1}, and for combined variability, σ_b = 0.82 m yr^{-1}. We compare these estimates with two other studies. First, ref. [162] reviewed records of glacier mass-balance observations around the world, and statistically analysed all with more than 10 years of observations. For glaciers with an annual accumulation of ~1.1 m yr^{-1}, they find a range of standard deviations of mass balance from 0.6 to 1.0 m yr^{-1}; our estimate lies squarely in the middle of this. Second, 10 years of observations from Zongo glacier in Bolivia, demonstrated a high correlation between annual-mean temperature and annual-mean mass balance ($r \sim 0.9$). The range in the observed annual-mean mass balance (i.e., max - min) is approximately 2.7 m yr^{-1}, and the range in observed annual-mean temperature is approximately 1.5 K[248]. This scales as -1.8 m yr^{-1} per 1 K of warming. Our calculations for Palcaraju give -1.5 m yr^{-1} per 1 K of warming from variability, and -2.0 m yr^{-1} per 1 K from a step change in temperature.

Climate forcing	Preindustrial geometry	Modern geometry	Notes
Δz_{ela} for ΔT = +1.3 K	+235 m	+235 m	Agrees with refs. [112] and [157].
Δb for ΔT = +1.3 K	-2.8 m yr^{-1}	-2.7 m yr^{-1}	Ref. [248] finds a range in b of 2.7 m yr^{-1} for a range in T of 1.5 K in 10 years of observations, for Zongo glacier, Bolivia.
Δz_{ela} for ΔP = +0.1 m yr^{-1}	-21 m	-13 m	
Δb for ΔP = +0.1 m yr^{-1}	+0.1 m yr^{-1}	+0.1 m yr^{-1}	
σ_{ela} for σ_T = 0.55 K	100 m	100 m	Ref. [112] estimate ~85 m for Cordillera Blanca.
σ_{ela} for σ_P = 0.2 m yr^{-1}	22 m	19 m	Ref. [112] estimate ~30 m for Cordillera Blanca.
σ_{ela} combined. (i.e., $(\sigma_{b,T}^2+\sigma_{b,P}^2)^{1/2}$)	102 m	102 m	Ref. [112] estimate ~90 m for Cordillera Blanca.
σ_b for σ_T = 0.55 K	0.74 m yr^{-1}	0.80 m yr^{-1}	
σ_b for σ_P = 0.2 m yr^{-1}	0.19 m yr^{-1}	0.20 m yr^{-1}	
σ_b combined. (i.e., $(\sigma_{b,T}^2+\sigma_{b,P}^2)^{1/2}$)	0.76 m yr^{-1}	0.82 m yr^{-1}	For observed glaciers with annual accumulation of ~1.1 m yr^{-1}, Medwedeff and Roe (2017) find a range in σ_b of 0.6 to 1 m yr^{-1}

Table S3: Sensitivity of ELA (z_{ela}) and mass balance (b) to climate forcing in annual-mean temperature (T) and precipitation (P), calculated for both the preindustrial and modern profiles of Palcaraju glacier (Fig. 2 in the main text). Calculations denoted with a Δ represent step-changes in climate; calculations denoted with a σ denote one standard deviation of variability. The values of ΔT, σ_T, and σ_P are based on observations. The value of ΔP is based on an extreme assumption about change in precipitation since preindustrial.

GLOF Hazard Assessment

We perform a GLOF hazard assessment for Lake Palcacocha using two methodologies, as described in the main text and Methods. Table S2 shows the data used in the GLOF hazard assessment following the methodology of ref. [167], for our reconstruction of the 19th-Century glacier and lake and in the present day.

The overall hazard increases from medium to very high. Table S3 shows our recalculated weight factors for the GLOF hazard assessment adapted from ref. [168]. We then provide our assessment of the characteristics of the glacier and lake which contribute to the GLOF hazard ranking. We find that the GLOF hazard stood at 'medium' in the 19th Century, and then increased to 'high' immediately prior to the 1941 GLOF. Present GLOF hazard is also 'high', according to this methodology. These methodologies are described in further detail in the Methods.

GLOF hazard assessment based on ref. [167].									
Criteria	**Weight factor**	**Pre-industrial**	**Source**	**Danger Value**	**Weighted pre-industrial**	**Present-day**	**Source**	**Danger Value**	**Weighted present day**
Mother glacier area (km^2)	0.070	>6.2	Definitely bigger than present, and in the highest danger value class	1.0	0.07	6.2	GLIMS: http://www.glims.org/maps/info.html?anlys_id=312068	1.0	0.070
Distance between lake and glacier terminus (m)	0.270	0	Our modelling / images in ref. [146]	1.0	0.27	0	Photos	1.0	0.270
Slope between lake and glacier (°)	0.220	8.3	Model reconstruction (Fig. 3a). Gradient is the section of glacier surface with 500m horizontal distance from the lake surface	0.25	0.06	35	Model reconstruction of present-day glacier geometry	1.0	0.220

Mean slope of moraine dam (°)	0.195	24	Refs. [6,138]	1.0	0.20	8.5	Ref. [6]	0.25	0.048
Mother glacier snout steepness (°)	0.245	8.3	Model reconstruction	0.25	0.06	35	Model reconstruction	1.0	0.245
TOTAL					**0.65**				**0.85**

GLOF hazard assessment minimum thresholds		
	Low	0
	Medium	0.5
	High	0.7
	Very high	0.8

Table S4: GLOF hazard assessment for our reconstruction of the pre-industrial and the present configurations of Lake Palcacocha and Palcaraju glacier, using the quantitative methodology of ref. [167]*. Weighting factors and danger value classes are given in ref.* [167] *and described in the Methods section of the main text.*

1

GLOF hazard assessment based on ref. [168]							
Criteria	**Weight factor**	**Pre-industrial**	**Weighted pre-industrial**	**1941**	**Weighted 1941**	**Present-day**	**Weighted present-day**
Lake area change	0.2000	0	0.0000	1	0.2000	2	0.4000

Possibility of ice avalanche into lake	0.1778	1	0.1778	1	0.1778	1	0.1778
Possibility of rockfall / avalanche into lake	0.1556	1	0.1556	1	0.1556	1	0.1556
Ice-cored moraine?	0.1333	0	0.0000	0	0.0000	0	0.0000
Debris flow	0.1111	1	0.1111	1	0.1111	1	0.1111
Flash flood	0.0889	0	0.0000	0	0.0000	0	0.0000
Direct contact with glacier?	0.0667	1	0.0667	1	0.0667	1	0.0667
Lake area	0.0444	1.5	0.0667	1	0.0444	1.5	0.0667
Glacier shrinkage	0.0222	0	0.0000	1	0.0222	1	0.0222
TOTAL	**1.0000**		**0.5778**		**0.7778**		**1.0000**

GLOF hazard assessment minimum thresholds		
	Very low	0
	Low	0.1000
	Medium	0.3833
	High	0.6667

Table S5: GLOF hazard assessment for our reconstruction of the pre-industrial, 1941 and configurations of Lake Palcacocha and Palcaraju glacier, using an adapted version (see Methods) of the semi-quantitative methodology presented in ref. [168]*. Weighting factors and hazard level thresholds were recalculated based on the methodology used by ref.* [168]*.*

8.4 Supplementary materials to Paper 3

Quantifying heat-related mortality attributable to human-induced climate change

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Supplementary Information

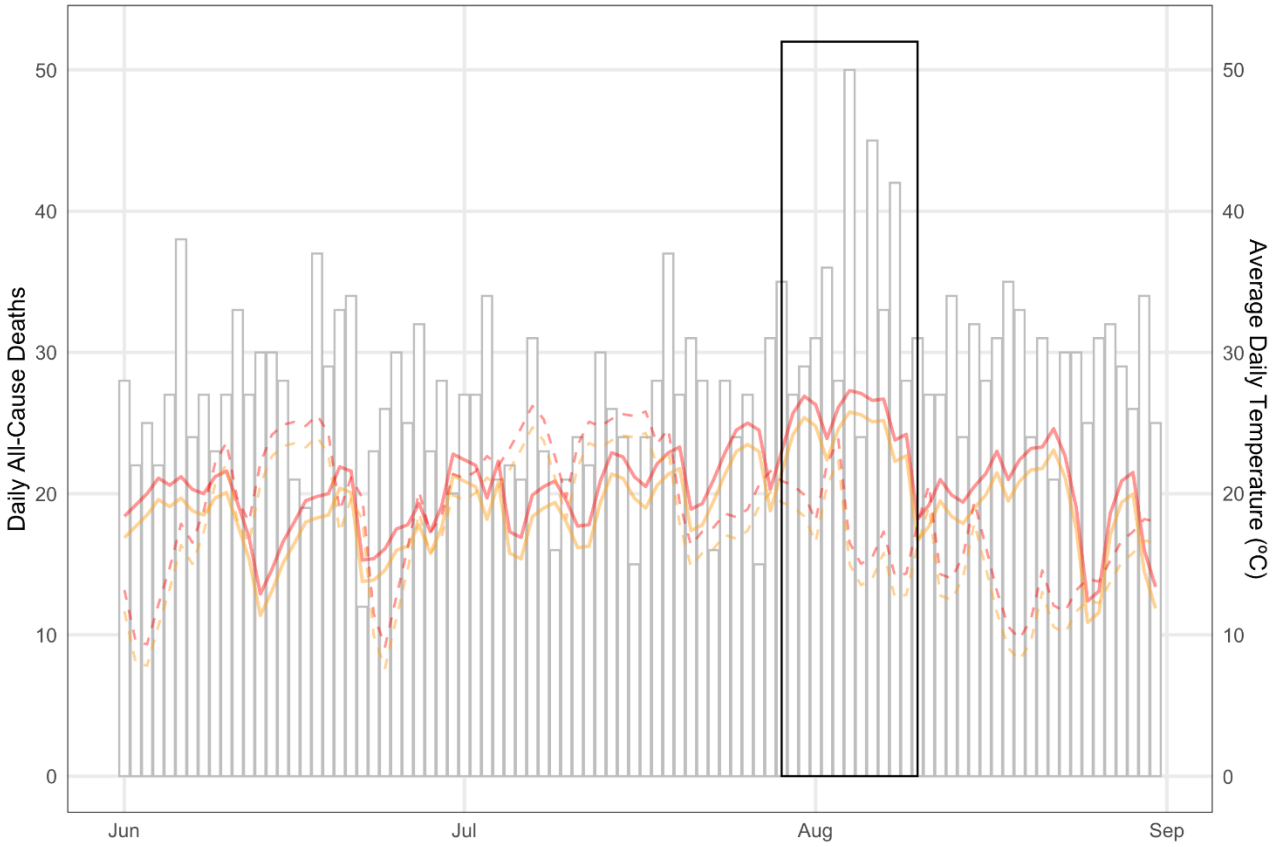


Figure S1: Daily all-cause mortality and daily-mean temperatures for the historical (red) and counterfactual (orange) scenarios based on the method applied in this study (solid lines) and the approach taken by Vicedo-Cabrera et al. (2021; dashed lines) [28] and for the CMCC-ESM2 model in each case. The dashed lines show historical and historical-natural data from the CMCC-ESM2 model simulations, bias corrected using the same statistical approach [249] applied in ref [28].

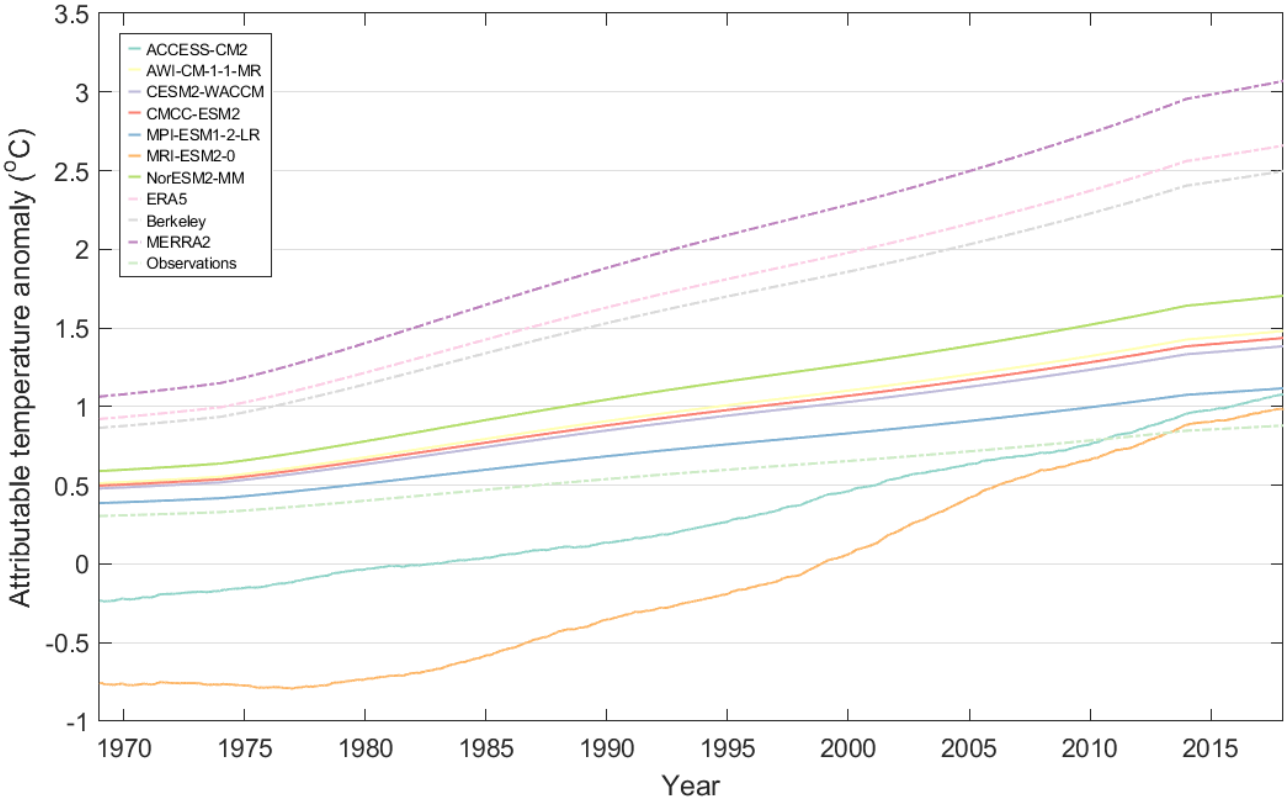


Figure S2: Temperature anomaly attributable to anthropogenic climate change for 1969-2018 in climate-model timeseries, reanalysis and station observations. Temperature anomalies are the difference between factual and counterfactual timeseries in each of the observed and model datasets, based on a baseline period of 1989-2018. Observation-based (reanalysis and station records) data are shown as dashed lines, whereas model data are presented as solid lines. The negative anomaly seen in two of the model timeseries during the early portion of the displayed data (ACCESS-CM2 and MRI-ESM2-MM) is explained in Methods ('Constructing the counterfactual temperatures'). By the end of the study period, all models' attributable temperature anomalies lie within the range of the observation-based datasets.

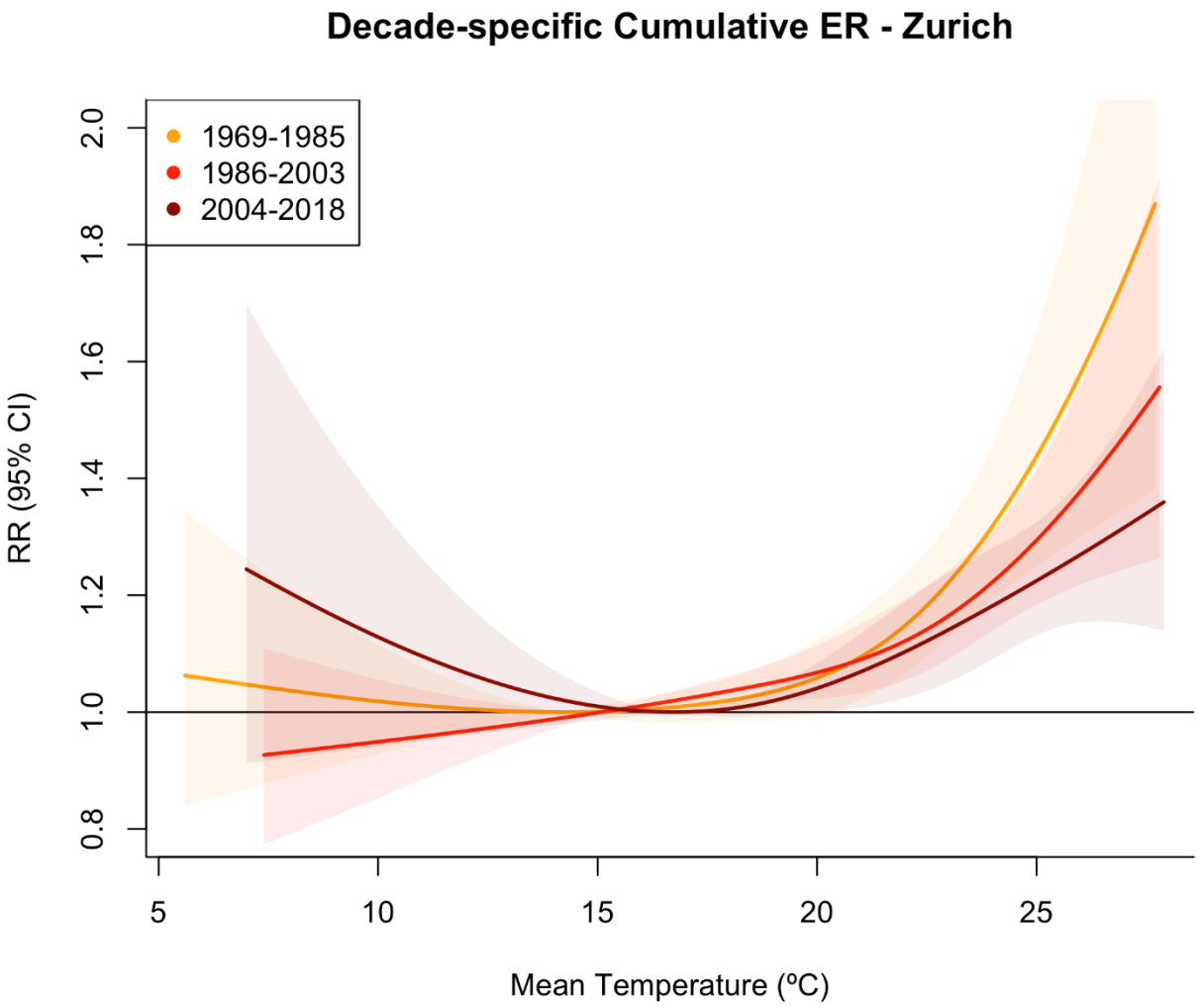


Figure S3: Exposure-response associations derived from observed daily-mean temperature and mortality, for 1969-1985, 1986-2003, and 2004-2018. 5-95% empirical confidence intervals are represented by the shaded areas.

Models selected in analysis	Non-selected models
ACCESS.CM2	ACCESS-ESM1-5
AWI-CM-1-1-MR	CESM2
CESM2-WACCM	CEMCC-CM2-SR5
CMCC-ESM2	FGOALS-g3
MPI-ESM1-2-LR	GFDL-ESM4
MRI-ESM2.0	INM-CM4-8
NorESM2-MM	INM-CM5-0
	MIROC6
	MIROC-ES2L
	NorESM2-LM
	TaiESM1

Table S1: CMIP6 models used in analysis showing those selected in the evaluation step and those excluded following evaluation.

Climate model	Institute	Spatial resolution (# of grid longitude by latitude)	Experimental ID used
ACCESS-CM2	CSIRO (Commonwealth Scientific and Industrial Research Organisation, Australia), ARCCSS (Australian Research Council Centre of Excellence for Climate System Science)	192 x 144	historical SSP5-8.5 hist-nat
AWI-CM-1-1-MR	Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Germany	384 x 192	historical SSP5-8.5
CESM2-WACCM	National Center for Atmospheric Research, Climate and Global Dynamics Laboratory, USA	288 x 192	historical SSP5-8.5
CMCC-ESM2	Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici, Italy	288 x 192	historical SSP5-8.5
MPI-ESM1-2-LR	Max Planck Institute for Meteorology, Alfred WegenerInstitute, Deutsches Klimarechenzentrum and DeutscherWetterdienst, Germany	192 x 96	historical SSP5-8.5
MRI-ESM2-0	Meteorological Research Institute, Tsukuba, Ibaraki 305-0052, Japan	320 x 160	historical SSP5-8.5 hist-nat
NorESM2-MM	NorESM Climate modeling Consortium consists of CICERO, MET-Norway, NERSC, NILU, UiB, UiO and UNI, Norway.	288 x 192	historical SSP5-8.5

Table S2: Detailed information for the climate models used for analysis in study.

Dataset (model run or reanalysis)	Central estimate	Confidence interval (lower)	Confidence interval (upper)
ACCESS.CM2	954	761	1140
AWI.CM.1.1.MR	1683	1339	2011
CESM2.WACCM	1585	1262	1893
CMCC.ESM2	1638	1304	1957
MPI.ESM1.2.LR	1306	1042	1555
MRI.ESM2.0	322	178	473
NorESM2.MM	1902	1512	2279
Station observations	1048	835	1243
ERA5	2746	2105	3329
Berkeley Earth	2613	2014	3157
MERRA2	3065	2325	3738
Observations synthesis	2363	914	3548
Model synthesis	1339	253	2104
Full synthesis	1712	276	3329

Table S3: Heat-related mortality attributable to anthropogenic climate change for each model and observation-based dataset, 1969-2018.

Dataset	Central estimate	Confidence interval (lower)	Confidence interval (upper)
ACCESS.CM2	0.79	0.63	0.94
AWI.CM.1.1.MR	1.39	1.11	1.66
CESM2.WACCM	1.31	1.04	1.57
CMCC.ESM2	1.35	1.08	1.62
MPI.ESM1.2.LR	1.08	0.86	1.29
MRI.ESM2.0	0.27	0.15	0.39
NorESM2.MM	1.57	1.25	1.88
Station observations	0.87	0.69	1.03
ERA5	2.27	1.74	2.75
Berkeley Earth	2.16	1.67	2.61
MERRA2	2.53	1.92	3.09
Observations synthesis	1.95	0.76	2.93
Model synthesis	1.11	0.21	1.74
Full synthesis	1.42	0.23	2.75

Table S4: Fraction of all-cause summer (June-August) mortality attributable to the impact of anthropogenic climate change on temperatures, 1969-2018.

	Single exposure-response	Adaptation	No-adaptation
Heat-related mortality (historical)	6217 (2825-9623)	6004 (2922-8694)	6742 (3696-9433)
Heat-related mortality (counterfactual)	4457 (1046-8051)	4236 (1618-7273)	4809 (2054-7970)
Attributable heat-related mortality	1712 (276-3329)	1725 (124-3623)	1890 (200-3875)
Heat-related mortality (% of all-cause mortality)	5.1 (2.3-8.0)	5 (2.4-7.2)	5.6 (3.1-7.8)
Counterfactual heat-related mortality (% of all-cause mortality)	3.7 (0.9-6.7)	3.5 (1.3-6.0)	4 (1.7-6.6)
Attributable heat-related mortality (% of all-cause mortality)	1.4 (0.2-2.8)	1.4 (0.1-3.0)	1.6 (0.2-3.2)
Attributable portion of heat-related mortality (%)	27.5	28.7	28

Table S5: Heat-related mortality calculated using the single exposure-response association (derived from all observed temperatures and mortality) and the time-varying exposure-response associations for the 'adaptation' and 'no-adaptation' scenarios. As described in the main text, the exposure-response association calculated for 1986-2003 is also applied to 2004-2018 in the 'no-adaptation' scenario. Bracketed values are the 5-95% empirical confidence intervals.

Company	Cumulative emissions 1854-2010 ($GtCO_2e$)	Percent of global anthropogenic emissions (1751-2010)	Attributable heat-related mortality, Zürich 1969-2018
Chevron	51.1	3.52	61
ExxonMobil	46.7	3.22	56
Saudi Aramco	46.0	3.17	55
BP	35.8	2.47	43
Gazprom	32.1	2.22	38
Royal Dutch / Shell	30.8	2.12	37
National Iranian Oil Company	29.1	2.01	35
Pemex	20.0	1.38	24
Conoco Philips	16.9	1.16	20
Petroleos de Venezuela	16.2	1.11	19

Table S6: Cumulative 1854-2010 scope 1,2, & 3 emissions attributable to the ten highest-emitting investor- and state-owned companies, the proportion of historical anthropogenic greenhouse gas emissions attributable to these actors, and the estimated heat-related mortality attributable to each company for the Canton of Zürich over 1969-2018. Historical emissions data are sourced from ref. [7].

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