Carbon majors and the scientific case for climate liability

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Writing in these pages in 2003, Myles Allen considered the limits of climate science and posed an essential question[1]: "Will it ever be possible to sue anyone for damaging the climate?" Twenty years later, we argue that the scientific case for climate liability is closed[2]. Here we detail the scientific and legal implications of an "end-to-end attribution" that quantitatively links specific corporate emitters to specific economic losses from warming[3–5]. Using emissions data from major fossil fuel firms[6], peer-reviewed attribution methods[7], and recent advances in empirical climate economics[8], we show—for the first time—the billions in economic losses directly attributable to the extreme heat caused by emissions from individual fossil fuel firms. We link Chevron, for example, to more than US$900 billion in heat-related losses over 1991-2020, with those burdens disproportionately falling on tropical regions least culpable for warming. While these linkages were not possible to draw 20 years ago when Allen first considered the legal implications of attribution science, they are now. Science is no longer an obstacle to the justiciability of climate liability claims.

As soon as climate attribution emerged as a legitimate field of inquiry, scholars both scientific[1] and legal[9] raised questions about whether climate liability claims could be pursued via common law[10]. Extreme weather events—floods, droughts, extreme heat, among others—harm people. These events upend lives, undermine livelihoods, and damage property. To the extent that such extremes could be attributed to climate change, the logic goes, injured parties could use courts to seek restitution or injunctive relief. Over the last twenty years or so, science and law have been engaging a set of challenges that take climate liability from being Allen's 2003 thought experiment into a realistic practice.

Scientifically, the focus has been on advances in attribution, in particular developing standardized methods that have codified a scientific consensus on the role climate change plays in amplifying extreme events[11]. Such consensus attribution methods might meet legal standards for admissibility[12], and have been applied to a variety of events[13–15] from heat waves[16,17], to droughts[18,19], to floods[20], with many events now being attributed in near-real-time[21]. By revealing the human fingerprint on events previously thought to be "acts of God," attribution science has helped make climate change legally legible[22–25].

Legally, much of the focus has been on assessing whether climate attribution is compatible with existing frameworks of causation and standing, and many of these questions are currently being adjudicated in courts around the world. In fact, since Allen first theorized them, a wave of climate lawsuits has emerged. More than 100 climate-related lawsuits have been filed each year since 2017, with far more anticipated, many seeking to hold someone to account for the damage wrought by warming[5]. For example, in 2017, the city of Oakland, CA sued British Petroleum and several other fossil fuel companies for causing sea level rise along the California coast[26]. New York City and Rhode Island have both brought similar claims[27,28]. Firms like ExxonMobil have had myriad suits brought against them, with plaintiffs ranging from residents of flooded Alaskan villages to Puerto Rican municipalities damaged by Hurricanes Irma and Maria[29,30]. Most of these cases have been dismissed and no suit has succeeded. Yet litigation shows no signs of slowing[31]. As extreme events intensify and damages accumulate—and as political action on climate change lags the urgency of the crisis—more people are turning to the legal system for relief[31]. There is talk of a "coming tsunami of climate litigation" for which courts are woefully unprepared[32]. This reality has led thoughtful nonprofits like the Environmental Law Institute to develop programs to educate judges in climate science and attribution to prepare for this coming onslaught[33].

In this Perspective, we detail scientific and legal hurdles to climate liability, and illustrate how a climate attribution that goes from emissions to impact at the corporate scale is now possible. Using climate models and quantitative social science, we estimate the economic losses that regions around the world have suffered due to the extreme heat caused by emissions from major fossil fuel firms ("carbon majors") over the last 30 years. We argue that while such an "end-to-end" attribution is now possible and may provide legal clarity in some respects, the question of whether climate liability is justiciable remains open, and must invariably be resolved in courts around the world in the coming years and decades.

The requirement of "but for" causation

The scientific and legal enterprises share many similarities: they are equally consumed with establishing facts, drawing lines of evidence, proving causation, building theories, leveraging frameworks, and exercising prudence. But there are crucial differences as well. As a practice, science is loath to render final judgement, instead always updating in the face of new evidence. In contrast, the doctrine of legal judgement is finality, with decisions becoming precedents and precedents becoming the basis for future judgements. Another distinction is that the burden of proof is higher in science than in law[34], as science works to falsify hypotheses and jettison theories[35], while many legal judgements, such as those in U.S. civil law, seek only a preponderance of evidence (i.e., that something is more likely than not).

These distinctions between scientific and legal judgment are important when it comes to questions of climate liability. It implies, for example, that what constitutes an advance on the scientific side (e.g., attribution) does not necessarily resolve questions on the legal side (e.g., causation, standing). They are different enterprises with different goals. Yet there is reason to believe that advances in scientific attribution of climate damages can help clarify the set of legal paths to climate liability claims, in part by better articulating "but for" causation[9].

To sue over an injury, a litigant must be able to demonstrate "but for" causation: without the actions of the defendant, the plaintiff would not have been injured[9]. This task is straightforward in many cases, such as car accidents, workplace negligence, and the like. But in the context of climate change impacts, it is more difficult, as a plaintiff must link "general" to "specific" causation. General causation is concerned with whether something causes some type of harm, such as the way asbestos causes increased cancer risk. Specific causation, on the other hand, considers whether a defendant's actions caused the specific injury brought by the litigant: whether a worker with cancer was chronically exposed to asbestos in the workplace, for example. Both general and specific causation are needed. In his Perspective, Allen hypothesized how climate attribution might meet these standards: If global warming has tripled the risk of a flood event, Allen notes, then such warming is responsible for two-thirds of the risk of that event, and thus contributors are liable for two-thirds of its harm[1]. Such an argument, however, has scientific and legal gaps. Linking extremes events to global warming writ large does not prove the causal role of a specific actor in causing damages to a specific claimant[3,24]. The role of an individual contributor to warming must be isolated and changes in physical extreme events do not necessarily imply the particularized human or socioeconomic harms that would provide legal standing.

Hurricane Maria, the subject of a recent suit by Puerto Rican municipalities[29], provides a clarifying example. Peer-reviewed research that used climate models to compare Maria's observed rainfall to that which would have occurred absent climate change (i.e., in a "counterfactual" climate) has shown that human-caused warming intensified rainfall from the hurricane[36]. While valuable, however, such analysis does not resolve "but for" causation[37]; it is not clear, for example, how much ExxonMobil, specifically, contributed to such rainfall intensification. Moreover, it is unknown how the amount of rainfall translated into socioeconomic injury from the hurricane. Nonlinearities in how people and societies respond to climate stress make it difficult to extrapolate event attribution results to an individual actor's responsibility for climate damages[5,38]. Each of these open questions mean that the causation requirement has posed a major barrier to climate-related litigation to date[4,9,22,23,39]. Scientific advances that resolve this barrier, illustrating clear causal linkages all the way from emitters to impacts, have been termed the "Holy Grail" of climate litigation[39].

The science required for "but for" causation is "end-to-end" attribution: linking specific emissions to specific damages[3–5]. Such an analysis would go beyond the "fraction of attributable risk" framework proposed by Allen's 2003 piece[1] and often used in attribution studies[40], instead directly quantifying the harm caused by a specific actor's emissions. Yet this is not a trivial task. The causal chain from emissions to impacts is nonlinear[38] and uncertainties compound at each step from emissions, to changes in atmospheric greenhouse gas concentrations, to warming, and finally to concrete socioeconomic impacts[41]. Moreover, emissions and damages are dislocated in space and time—a flood or drought from such emissions could occur on the other side of the Earth from where the carbon was originally emitted, and damages could happen months, years, or decades after such carbon was originally pulsed to the atmosphere[42].

That being said, while such an attribution framework has long been thought to be beyond the limits of current scientific understanding, recent advances in multiple fields now make this attribution possible. Here we discuss these advances and illustrate their application to major fossil fuel firms by leveraging a peer-reviewed end-to-end attribution framework[7].

Scientific advances enabling "end-to-end" climate attribution

In building the causal chain from specific emissions to specific injury, we note two important advances that make this goal scientifically tractable. Firstly, science can more confidently establish the connection between individual emitters and resulting climate change. Secondly, social science can more confidently establish the connection between local climate change and socioeconomic outcomes.

On the first, "source attribution" research[3] has linked emissions from countries[43–45] and carbon majors[6] to warming and associated impacts like sea level rise[46] and ocean acidification[47]. Recent efforts also include linking individual countries' emissions to extreme climate events themselves[48–50], but not necessarily the human or socioeconomic impacts of those events. Source attribution typically relies on using an emissions-driven climate model to simulate the observed and counterfactual climates, where the latter is the same as the observed save for the removal of one emitter's time-varying emissions (i.e., a "leave-one-out" experiment). The difference between these two simulations represents the contribution of the left-out emitter and accords with the "but for" test of causation[9]: *but for the emissions of said actor, the climate would have been thus*, for example. One could perform these simulations with a fully coupled Earth system model[51], but such models are opaque and computationally expensive, especially when driven by emissions rather than with prescribed greenhouse gas concentrations. An alternative, computationally tractable approach is to use reduced-complexity climate models (RCMs) that simulate the low-dimensional behavior of the Earth system using a smaller number of equations.

RCMs like MAGICC[52] and FaIR[53,54] have long been part of the consensus methods used in the Intergovernmental Panel on Climate Change (IPCC) assessment reports[55], simulating particular mitigation pathways[56] or individual contributions to global temperature change[43,44]. For example, in recent work[7], we used FaIR to simulate country-level contributions to global mean temperature change, efficiently sampling parametric uncertainty in the carbon cycle 250 times for each country. The result was more than 40,000 unique simulations, all performed in less than two hours. The key drawback of RCMs is that they are zero-dimensional, lacking spatial information. Leveraging well-vetted methods that statistically relate global and local climates, such as pattern scaling[57–59], overcomes this shortfall, allowing scientists to draw maps of local temperature changes as a function of global temperature changes[60]. Together, the use of RCMs and pattern scaling allow researchers to link the contributions of individual emitters to local temperature changes across the globe in an efficient, transparent, and reproducible manner.[7,50]. Local climate changes due to individual emitters do not imply particularized injuries to people, however. In order to fully connect individual emitters to the impacts of their emissions, researchers must quantify the economic or social impacts of these local climate changes.

Enter the second major advance enabling end-to-end attribution, that of more robust quantifications of the socioeconomic impacts of climate change[61]. Applying metrics like the “fraction of attributable risk” that Allen posited are not appropriate for quantifying the influence of climate change on human impacts[38,62], though such approaches have been applied to impacts such as cyclone losses[63,64]. There are nonlinearities and complexities associated with quantifying the human response to extreme events: a levee may be resilient up to some threshold of rainfall or storm surge, for example, but just beyond that threshold, a catastrophic flood occurs. Such nonlinearities mean more complex and tailored approaches are necessary to connect greenhouse gas emissions to socioeconomic losses, to meet the demands of “but for” causation. Here, we draw on recent peer-reviewed work that uses econometric methods to infer general causal relationships between climate hazards and measurable human outcomes such as income loss[65,66]. For example, researchers have used such empirical methods to show that extreme climate conditions reduce agricultural yields[67], depress labor supply[68] and increase human mortality[69,70]. More recently, global macro-level studies have connected increases in temperature to reductions in economic growth[71–73]. In the context of attribution, these general causal relationships have then been applied to ascribe specific causation, quantifying the costs of climate-driven flooding[74], crop losses[75], and reduced global economic output from increases in average[76] and extreme[8] temperatures.

Here we leverage the latter finding, showing that emissions traceable to carbon majors have caused attributable increases in heat wave intensity globally, and that the additional heat wave intensity from those emissions has caused quantifiable income losses for people in subnational regions around the world.

End-to-end attribution for carbon majors

Holding fossil fuel companies accountable mirrors longstanding efforts to hold other industries, like tobacco[77], pharmaceuticals[78], and automotives[79] liable under legal frameworks like the duty of care, public nuisance, or strict liability. In particular, the oil, coal, and gas extracted by major fossil fuel companies have produced substantial emissions of carbon dioxide and methane over the last 100 years (Fig. 1a). For example, using data produced by Heede[6], we show that Chevron has been responsible for an average of 113 MtC yr^{-1} in emissions over 1991-2020, with a cumulative total of more than 14 GtC since 1912. ExxonMobil, similarly, has been responsible for 161 MtC yr^{-1} since 1991, and more than 13 GtC cumulatively since 1884. (The emissions start date for different firms differs due to the varying availability of records.)

To link these firms to the economic impacts of their emissions, we leverage peer-reviewed end-to-end attribution research[7] that outlines three steps: We use the FaIR RCM to translate firm-level emissions into global mean temperature changes (Fig. 1b), apply pattern scaling to calculate resultant changes in local extreme heat in subnational regions, defined as the temperature of the five hottest days in each year, or "Tx5d" (Fig. 1c), and apply an econometric damage function to calculate income changes due to these changes in extreme heat[8] (Fig. 1d).

We first simulate historical global mean surface temperature (GMST) change using total emissions with FaIR v2.1.0, providing the observed benchmark against which we compare our "counterfactual" firm-level leave-one-out simulations. For the latter, we re-simulate GMST change, this time subtracting each firm's CO_2 and CH_4 emissions from the model forcing. The difference between the observed and each firm's counterfactual simulation represents the GMST change attributable to that firm. For each firm, we perform 250 simulations, sampling the carbon cycle parameters in FaIR following Table 5 in Leach et al.[80]. The results from these simulations illustrate that each of the five carbon majors shown in Fig. 1a has made small, yet attributable contributions to GMST change (Fig. 1b). Over 1991-2020, we find that Chevron's contribution averaged 0.024 °C, while ExxonMobil's contribution averaged 0.021 °C. Most recently, Saudi Aramco has made the largest contributions to 2020 temperature change (0.031 °C) due to its substantial recent emissions (Fig. 1a). Varying carbon cycle strength in FaIR results in a range of outcomes for each firm, but this range is small relative to the overall magnitude of each firm's contribution (Fig. 1b).

We then translate these FaIR-based GMST change time series into spatiotemporal patterns of Tx5d change using pattern scaling coefficients estimated from 80 Earth system model simulations from the "historical" and "historical-natural" experiments run as part of the sixth phase of the Coupled Model Intercomparison Project (CMIP6). Taking the difference between the historical and natural simulations yields the anthropogenic contribution to GMST and Tx5d change, and linearly regressing anthropogenic Tx5d change onto anthropogenic GMST change yields a pattern scaling coefficient: degree of local Tx5d change per degree of GMST change. Applying these coefficients to the firm-level sets of FaIR simulations yields Tx5d change due to each carbon major (Fig. 1c). On average, Chevron is responsible for a 0.04 °C increase in average Tx5d values over 1991-2020 and ExxonMobil is responsible for 0.035 °C. Convolving uncertainty from the FaIR simulations with the pattern scaling coefficients across the CMIP6 simulations yields a wide range of outcomes, which we show using IPCC definitions[81]. It is virtually certain, for example, that Chevron's contribution to global average Tx5d change lies between 0.019 °C and 0.064 °C. Critically, despite this large range, none of the five firms have 99% ranges that include zero, meaning that it is virtually certain that all of them have increased the intensity of extreme heat globally via their emissions.

Finally, we use an econometric damage function that generalizes the relationship between changes in extreme heat intensity and economic growth[8] to estimate the economic consequences of firm-level changes in Tx5d. This damage function was derived using a panel regression of Tx5d and economic growth in a global sample of subnational regions[8]. The spatial pattern of heat-driven economic changes suggests a deep global inequality: warm regions least culpable for emissions suffer economically from extreme heat, while in the temperate regions where most global emissions have originated, the effect is minimal or positive (Fig. 1d). We calculate economic damages in both the historical simulations and the leave-one-out simulations, then take the difference to calculate economic damages attributable to the emissions from carbon majors. We use a Kolmogorov-Smirnov test in each region and year, testing the distribution of historical damage against the distribution of damage without the changes due to a given firm[7]. If these two distributions are statistically distinct ($p < 0.05$), the firm has made significant and quantifiable "but for" contributions to economic losses. These distributions account for the interacting range of outcomes among the FaIR simulations, pattern scaling, and damage function estimates, ensuring that we are responsibly propagating uncertainty throughout each step of the analysis. Finally, because changes in annual mean temperature moderate the effect of Tx5d change, we perform a similar pattern scaling analysis with regional annual mean temperature. Following previous work, the final damages calculations incorporate both changes in Tx5d itself as well as changes in the underlying annual mean temperature values that moderate the effect of Tx5d[8].

Our end-to-end attribution shows that "but for" the extreme heat caused by the emissions of these five carbon majors, the global economy would be billions of dollars richer over the last 30 years (Fig. 2). Chevron is responsible for the greatest extreme heat damage, with an average of $962 billion in losses traced to its emissions of CO_2 and CH_4. ExxonMobil is responsible for $317B, and BP, Saudi Aramco, and Shell are each responsible for >$9B (Fig. 2a). Ranges in these damage estimates can be large, due to the convolution of carbon cycle and response uncertainties in the FaIR simulations, and structural uncertainties in the pattern scaling and damage function. Yet in all cases, the 99% range for each of the five firms considered here does not include zero (Fig. 2a), indicating that it is virtually certain that each firm has made statistically attributable contributions to global heat-driven losses. Note that we account for the rebound effect shown in previous work, whereby the effect of extreme heat appears to be recovered after 2-3 years, meaning that we do not assume impacts on economic growth to be permanent[8].

The power of this approach is that we can estimate subnational losses, the spatial structure of which we present in Figure 2b. Together, the five carbon-emitting firms shown in Fig. 2a have driven annual reductions of GDP per capita exceeding 0.5% across much of the tropics, with the most severe impacts in South America, Africa, and Southeast Asia. By contrast, the United States and Europe—where Chevron, ExxonMobil, BP, and Shell are headquartered—have experienced far milder costs from historical extreme heat.

Other investor- or state-owned firms have also made important contributions to global emissions (e.g., Gazprom, Total Energies, ConocoPhillips), but we find that that their emissions are either small enough or recent enough that their contributions to heat-driven damages are not statistically significant. Critically, however, this lack of statistical significance does not mean these firms' emissions have not had important global economic effects. Our statistical test uses the canonical 5% level for significance (i.e., $p < 0.05$), but this standard may be overly stringent compared to legal standards for the preponderance of evidence[34], and relaxing this standard might yield significant damages for many more firms. Additionally, local extreme heat in subnational regions is but one of the myriad economic costs of warming, and these firms may have made substantial contributions to other costly hazards such as tropical cyclones, wildfires, or other underexamined risks[82], all of which, if estimated, could yield attributable harms adding to the firm-level tally of attributable damage.

These results illustrate, for the first time, the global economic toll that individual fossil fuel firms have caused due to the warming from their emissions of carbon dioxide and methane. Our framework integrates uncertainty at each step in the causal chain from emissions to global warming, global warming to local warming, and local warming to economic damages, and shows that the emissions of several carbon majors have caused large income losses from extreme heat at the local scale. The veil of plausible deniability these companies have hid behind for decades is threadbare.

Yet, in spite of the harm arising from emissions-driven extreme heat, fossil fuels have also driven immense economic prosperity over the last century. Our results do not reflect the benefits to economic growth that fossil-fueled energy has provided. Courts will need to carefully consider how the benefits of energy use are balanced against its externalities and the potential "duty of care" these firms have to the public[83]. Climate damages are a negative externality from fossil fuels not reflected in the current value of these firms. This disconnect is particularly strong given that these externalities have fallen most severely on the poorest people across the globe—those who have benefited least from fossil fuel use or have long been structurally exploited for its extraction[84]. More broadly, just as the benefits of a medication do not absolve a manufacturer who fails to warn its customers about side effects, the benefits of fossil fuel use do not mean that carbon majors should be absolved of liability for these devastating externalities[9].

Preparing for the coming wave of litigation

The validity of the scientific case for climate liability does not mean that such legal claims will succeed in court. Many essential questions remain. For example, it is not clear which emissions should be counted in attribution analyses. Such choices, which are the province of policymakers, lawyers, litigants, and courts, matter. The establishment of the United Nations Framework Convention on Climate Change in 1992 could represent a consensus "start date" for counting emissions[9]. It may be reasonable, therefore, to only hold actors accountable for emissions occurring after the scientific understanding of climate change became clear[44]. Yet fossil fuel firms have predicted climate change with striking accuracy since the 1970s[85] and have used their power and profit to cast doubt on the relationship between fossil fuels and warming for decades[86]. This reality represents a potential "duty of care" violation, implying that those firms could perhaps be held accountable for emissions occurring even before the international consensus on climate change emerged[83]. Social scientists using mixed methods including archival research[87], computational frame analysis[88], and interviews[89] have produced critical new evidence regarding the internal knowledge and public communications of fossil fuel firms, and future advances in this area, coupled with attribution analyses like ours, could add needed credibility to climate liability cases. Ultimately, however, these accounting and framing choices reside beyond the scope of science with the legal enterprise.

Even assuming that scientific questions are generally resolved, as we argue here, other legal and social barriers may prevent the latest scientific evidence from being used in legal contexts. Law lags science, with even existing consensus attribution science not being fully taken up in relevant cases[4]. Furthermore, even where the science may be relevant and usable, there are additional legal barriers. For example, many climate-related lawsuits have been dismissed because courts decided that they were displaced by legislation such as the Clean Air Act[90] or would require the court to inappropriately intervene in policymaking[91]. That being said, legal scholars have urged courts to take a more aggressive role in climate-related cases, and it is possible that scientific progress on causation, the development of new legal theories, or the urgent press of climate disaster will spur courts to embrace climate liability claims[92]. What is clear is that the road ahead on climate liability is long.

Despite such an uncertain legal future, we believe our results show that science is no longer an obstacle to the justiciability of climate liability claims. Our attribution framework is promising in this regard, as it can easily be applied to new actors, hazards, or emissions accounting schemes, such as emissions from the agricultural sector or the impacts of floods. As climate-economic science develops and new impacts are revealed such as the negative effects of extreme rainfall[93], these insights and their costs could be incorporated into an accounting of the full magnitude of climate damages attributable to individual carbon majors and other emitting actors. Legal claims may be brought against alternative sets of firms such as electricity utilities[94], and to the extent that emissions data are available for these firms, they could be easily incorporated into this attribution. In his prescience, Allen posited this moment 20 years ago, considering the extent to which scientific limitations represent an obstacle to climate liability. But science is no longer an obstacle; our legal and policy environments are.

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Competing interests

The authors declare no competing interests.

Author contributions

Both authors designed the analysis. C.W.C. performed the analysis. Both authors interpreted the results and wrote the paper.

Data and code availability

All data and code that support the findings of this study will be made available upon publication at github.com/ccallahan45.

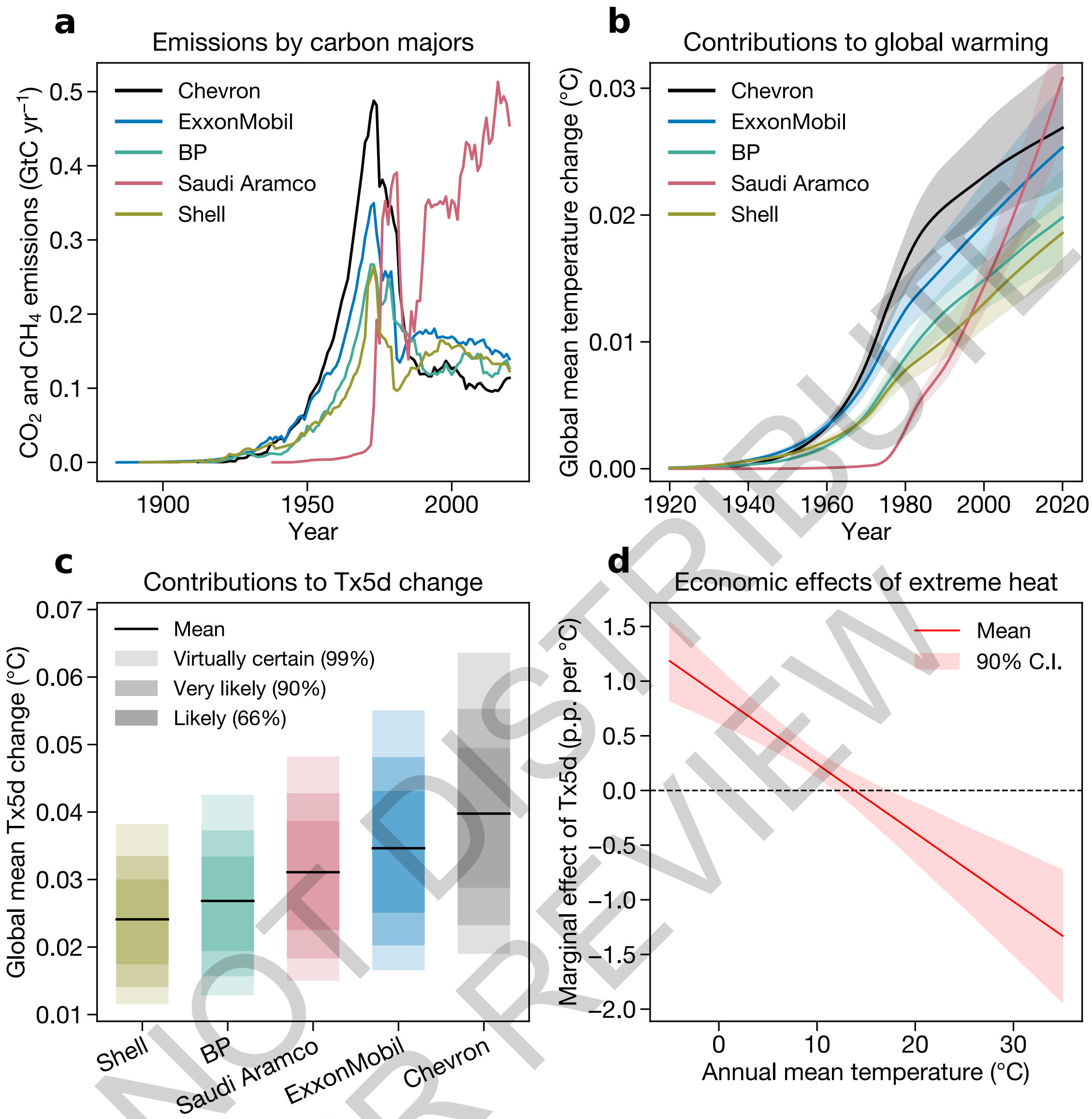

Fig. 1 | Linking economic losses from extreme heat to carbon majors. A) Emissions in total gigatons of carbon (GtC) per year of CO_2 and CH_4 from five major fossil fuel firms ("carbon majors"). B) Changes in global mean temperature resulting from the emissions of those carbon majors using FaIR simulations. Solid line shows the average across 250 simulations with varying carbon cycle strength and shading shows the 90% range across the ensemble. C) Changes in global average subnational Tx5d (temperature of the five hottest days in each year) from each carbon major, using a combination of FaIR simulations and pattern scaling. Solid line shows the mean and shading shows the various IPCC uncertainty ranges. Uncertainty is estimated as all combinations of FaIR simulations and pattern scaling estimates. D) Marginal economic effect of increases in Tx5d across a range of annual mean temperature values. Solid line shows the mean estimate and shading shows the 90% confidence interval.

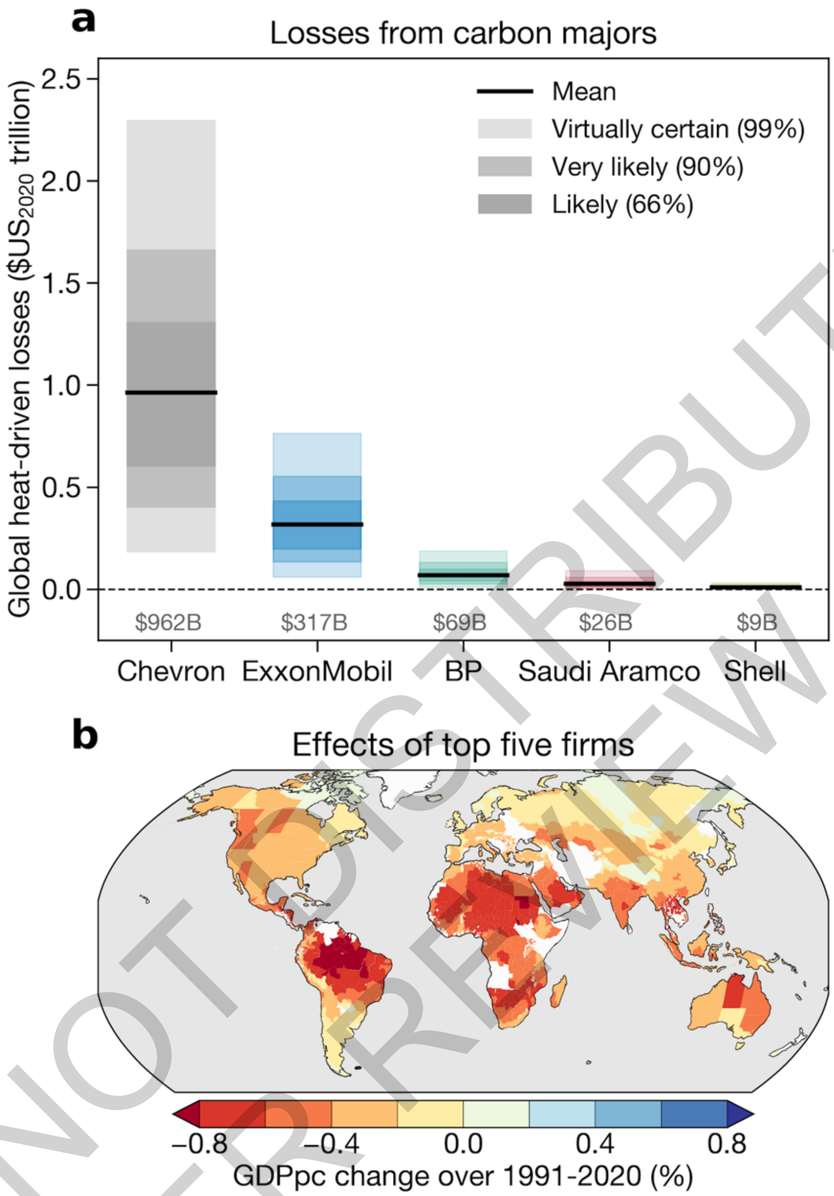

Fig. 2 | Economic losses from extreme heat linked to carbon majors. A) Global heat-driven economic losses linked to five fossil fuel firms. Black line shows the mean across 10,000 Monte Carlo simulations and gray shading denotes the IPCC likely (66%), very likely (90%), and virtually certain (99%) ranges. B) Average annual GDP per capita (GDPpc) change in subnational regions due to heat extremes driven by the combined emissions of the top five firms (shown in A). Other firms other than these five have been linked to shares of global emissions, but their effects are too small to be statistically significant in our framework.

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