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Extreme weather attribution: re-assessing company values using carbon emissions

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Abstract

Purpose – We present an accessible method of estimating companies' potential extreme weather liabilities, which can be used by policymakers, accountants, financial analysts, lenders and others to help assess climate risks.

Design/methodology/approach – Applying the emerging tool of emissions-based attribution, we estimate firms' climate liabilities by proposing an innovative Gordon's growth variant model for firms' potential extreme-weather-event liabilities.

Findings – Using our modelling approach, high-emitting firms' exposures appear considerable, potentially 3% of market capitalisation from single events. We estimate extreme-weather-event liability growth rates, showing the challenges of economic growth (accompanied by emissions) outstripping climate damages.

Research limitations/implications – The study provides a novel framework that can be used to assess the cost of extreme weather (EW) events for firms. Empirical testing is left to future research.

Practical implications – Our novel approach to assessing climate liability costs is accessible and straightforward to use by numerous stakeholders. Governments can assess carbon cost implications for high-emitting companies and contextualise corporate value implications against societal costs during policy design when considering responsibility (and cost) assignment to emitters. Accountants and analysts can explore company value sensitivities to extreme weather phenomena, emissions estimates and evolving societal positions on climate responsibility, including litigation. This will allow markets and decision-makers to better respond to corporate emissions' regulatory or financial consequences.

Originality/value – We include warming intensification, allowing financial analysts, accounting and risk management professionals to explore potential event liabilities, revised emissions estimates and evolving societal positions on climate damages responsibility (including litigation). Our model enables key economic stakeholders to more effectively integrate the financial impacts of corporate emissions into their decision-making processes and avoid a disruptive transition.

Keywords Climate policy, Climate risk, Emissions liability, Extreme weather, Climate liability, AGW intensification, Gordon's growth model

Paper type Conceptual paper

1. Introduction: Corporate climate risks and emissions liabilities

Estimating individual companies' climate-related risks and liabilities is of pressing concern for policymakers exploring possible regulatory changes to address a significant gap in our understanding of how such risks can be quantified and incorporated within financial decisions

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JEL Classification — G10, G2, Q5

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(Campiglio *et al.*, 2023; Condon, 2022; Frame *et al.*, 2020; Ilhan *et al.*, 2021) [1]. Analysing extreme weather (EW) events' considerable macroeconomic damages and their attribution to firms helps better assess corporate climate risks and promote economic sustainability. Financial impacts of anthropogenic global warming's (referred to as "GW" hereafter [2]) harmful consequences are well documented (Desmet and Rossi-Hansberg, 2015; Dafermos *et al.*, 2018; Gao *et al.*, 2024). Governments and regulators currently consider interventions aiming to correct the externality of greenhouse gas emissions (Griffin, 2020; NASEM, 2016).

Given that harmed parties are increasingly litigating against high-emitting firms (Setzer and Higham, 2022), authorities can no longer neglect climate consequences and must determine how aggressively to combat global warming. This includes addressing corporate emitters' potential liabilities and choosing the best possible approaches when considering new policies, investment and political effects (Barnett *et al.*, 2020; Griffin, 2020; Semieniuk *et al.*, 2021; Ilhan *et al.*, 2021; Stern *et al.*, 2022). The resulting policies and economic transformation have significant financial impacts for numerous economic agents, including investors, high-emitting firms' bank-lenders, and insurers. For example, consider existing frameworks such as the Task Force on Climate-Related Financial Disclosures (TCFD) and IFRS S2 [3]. Under these frameworks, accounting professionals must identify and manage climate risks for company annual reports disclosure purposes. However, this task appears highly problematic, especially for GW's extreme weather event damages, which investors fail to rationally anticipate and are attributable to individual firms' emissions (Griffin and Jaffe, 2019; NASEM, 2016). Furthermore, although investors demand higher climate risk premia for high-emission stocks, current literature shows that such risks appear far from fully priced into markets (Bolton and Kacperczyk, 2023; Condon, 2022; Stern *et al.*, 2022).

This article addresses this significant gap in the literature. It is motivated by investors' higher climate risk premia and accounting climate disclosure requirements for high-emission stocks. Current literature shows that climate liabilities are often mispriced (Thomä and Chenet, 2017; Ahairwe *et al.*, 2022). Furthermore, it is unclear how such liabilities can be readily incorporated in high-emitting firms' values for all aspects of policy decisions, asset pricing, valuations, and potential corporate defaults' estimation.

We address these problems by exploring companies' GW-related extreme weather liabilities emphasising climate research. Climate science connects human contributions to EW damages, allowing emitter liability attribution (Allen, 2003; Otto *et al.*, 2017). We extend attribution to companies, building on Rayer *et al.*'s (2023) responsibility share to encompass societal desire or ability to enforce responsibility, adding future GW intensification [4]. We innovatively integrate climate science within a conventional company/equity valuation framework in a practical, informative and theoretically robust manner [5]. Our proposed modelling approach is parsimonious [6], tractable, and conceptually insightful regarding emissions' EW climate response. It is also potentially generalisable across extreme weather climate phenomena, and falsifiable respecting linearly assumed GW intensification. Importantly, it reflects empirical climate data (Gabaix and Laibson, 2008) by highlighting the connections between firms' emissions and inexorable climate EW event response in terms of damages, periodicity, and increases in frequency (dynamic nature).

Although a few studies researching firms' climate liabilities are starting to propose some interesting approaches (with evident disparity between them), a gap remains around modelling liabilities within a conventional company/equity valuation framework. For example, Bolton and Kacperczyk (2021, 2023) use quantitative statistical methods to establish a largely qualitative result (higher current emissions associated with a higher carbon premium). Barnett *et al.* (2020) and Weyant (2017) consider the macroeconomic perspectives without linking to individual emitters, while Lott *et al.* (2021) examine how part of an EW event's damages can be attributed to individual persons. Thus, studies causally linking individual corporate emissions quantitatively to climate extreme weather damages are still lacking [7]. We address this gap by adapting Gordon's (1963) stock valuation model, to estimate firms' potential climate-related EW liabilities. We include climate research developments from the environmental science literature and calibrate our modelling approach to not overestimate attributable liabilities [8]. Currently, governments and insurers largely bear such costs. However, reacting to pressure to absorb increasing climate damages, they might eventually challenge the status quo as global climate-litigation cases between 2015 and 2022 have more than doubled (Setzer and Higham, 2022). Other emitter liability assignment mechanisms potentially include regulation, carbon taxation, carbon credit schemes, or social licence (Chameides and Oppenheimer, 2007; Griffin, 2020). Although cost extraction mechanisms are uncertain, analysts must factor these risks into corporate valuations.

Hence, the contribution of our study is twofold. First, we present a parsimonious, tractable, conceptually insightful method for accounting and financial professionals (including policymakers) to estimate emitting companies' potential climate extreme weather liabilities, recognising global warming intensification. By basing EW liabilities on established physical climate insights, we tie climate-related damages to emissions. Thus, enhancing financial markets' transparency and informational efficiency and helping investors anticipate regulatory changes and potential stock revaluations. This helps markets internalise emissions' uncosted externality. Secondly, we help explore liability sensitivities to future EW events, revised emissions estimates and evolving societal positions on climate damages responsibility, from carbon pricing, regulation or litigation. Our article demonstrates that quantified extreme weather damages can be linked to corporate emissions via established techniques. Also, the potential corporate emissions-linked EW liabilities are significant and apparently increasing. We suggest potential liabilities approximating 3% of market capitalisation for a hypothetical, yet representative, high-emitting company used as a case study. We argue that our modelling approach, although superficially simple, encapsulates physical climate insights, opening new research avenues for corporate valuation models, helping attribute the net cost of climate damages to firms' real economic activities.

The article is structured as follows. Section 2 reviews relevant literature on GW's economic impacts, damages and emissions-related climate liability. Section 3 outlines our methodology. In section 4, we develop our Gordon's model variant, EW event inputs (including damages and emissions attribution), climate-liability discount and growth rates. Section 5 examines the 2017 North Atlantic hurricane season, analysing events as isolated, regularly reoccurring or with GW intensification. Section 6 critically discusses our approach, including merits, potential weaknesses, supporting evidence, sensitivity studies and requirements. Section 7 concludes.

2. Literature review

Our literature review explores the related topics of GW's economic damages, integrated assessment models, climate litigation and companies' valuation responses.

2.1 Global warming and economic damages

Global warming may impact companies through channels including natural environment destruction, biodiversity loss, pandemics, loss of life and livelihoods (IPCC, 2021; Stern, 2006). Present emissions' rates suggest temperature increases of 3°C or more within a century (UNEP, 2020). Current warming is around 1.2° above pre-industrial levels and increasing (Haustein *et al.*, 2017), already promoting EW events and associated economic damages, potentially disrupting corporate activities. Table 1 introduces examples of recent extreme weather events, with economic damages in column D_E. Consequences will likely extend far beyond supply chain disruptions, or regulatory changes, as Stern *et al.* (2022) observe, fundamental structural changes to economies are required, including to energy systems, transport, cities and land-use.

As Table 1 shows, macroeconomic climate damages (D_E) appear considerable, with some individual event damages reaching up to $265bn. From 1989, using emissions data and a 2030

Table 1. Some recent historical extreme weather events

Event	Description	Event damages D_E	FAR	Growth rate, g (decimal)	Return period, R_0 (years)	Firm event liability, $L^{EW}_{H,0}$	$\frac{L^{EW}_{H,0}}{V_H}$
2010 Russian heatwave	Warmest July since records began. Return period reduced from 99 years (1960s) to 33 years (Otto *et al.*, 2012)	\$15bln	$\frac{2}{3}$	0.022	33	\$0.10bln	0.05%
2011 Thailand flooding	Worst flooding in past 50 years (EM-DAT, n.d., Promchote *et al.*, 2016; Rayer *et al.*, 2021)	\$52bln	0.575	0.032	15	\$1.6bln	0.8%
2015–2017 South African drought	Western Cape drought and possible Cape Town "day zero" (EM-DAT, n.d., Otto *et al.*, 2018b)	\$1.74bln	0.70	0.019	100	\$0.004bln	0.002%
2017 hurricane season including hurricane Harvey	Flooding. Precipitation intensities increased from 1-in-100-year events (late twentieth century) to 1-in-16-year events (Emanuel, 2017)	\$265bln	0.84	0.027	16	\$6.6bln	3%
2020 Siberian heatwave	Verkhoyansk June temperature of 38 °C (Sakha Republic, Russia) Probability increased at least 600-fold (Ciavarella *et al.*, 2021). Damage based on Sakha Republic permafrost degradation (Streletskiy *et al.*, 2019)	\$21.3bln	$\frac{599}{600}$	0.018	130	\$0.046bln	0.02%
2022 hurricane Ian	Charlotte and Lee Counties (Florida) and North Carolina, USA, 28 August to 2 October (NOAA, 2023). Attribution estimated from 2017 hurricane season	\$115bln	0.84	0.027	16	\$2.9bln	1%
2023 Mediterranean heat dome	July Mediterranean extreme heat. Probability increased at least 1000-fold (Zachariah *et al.*, 2023). Estimated GDP percentage country costs: Greece 0.9pp, Spain 1.0pp, Italy 0.5pp, and France 0.1pp (Subran *et al.*, 2023) 2022 GDP figures (World Bank, n.d.) imply \$29bn damages	\$29bln	$\frac{999}{1000}$	0.017	10	\$0.78bln	0.4%
2023 US heat dome	July southern USA heatwave. Probability increased at least 1000-fold (Zachariah *et al.*, 2023). Estimated costs of 0.3pp of US GDP (Subran *et al.*, 2023) 2022 GDP figures (World Bank, n.d.) imply \$76bn damages	\$76bln	$\frac{999}{1000}$	0.017	15	\$1.4bln	0.7%

Source(s): The authors

$50 carbon price discounted at 2% annually, Mitchell *et al.* (2021) estimate global liabilities of $26tn. More conservatively, Callahan and Mankin (2022) estimate that since 1990, collectively, the top five emitting countries (the United States, China, Russia, Brazil and India) caused $6tn in income losses (comparable to 11% of annual global gross domestic product). Discussing legal obligations, based on emissions, Tol and Verheyen (2004) estimate that OECD countries' damages responsibility might amount to 4% of gross domestic product [9].

2.2 Integrated assessment models

Climate-related risks are often explored using integrated assessment models (IAMs), emphasising economic and policy perspectives (Ackerman *et al.*, 2009; Weyant, 2017). IAMs are multi-equation computer simulations taking results from atmospheric general circulation models to assess climate policies' benefits and costs to identify "optimal" responses. IAMs differ significantly in their complexity, ranging from fairly simple models, such as those proposed by Nordhaus (2014), to models including thousands of equations covering physics, chemistry, biology, and economics (Reilly *et al.*, 2012). All include economic and natural processes producing greenhouse gases to simulate their effect on the global carbon cycle, climate, sea level and other natural systems (Weyant, 2017). Ackerman *et al.* (2009) consider most IAMs' results surprising, as, contrary to many scientists' recommendations for strong targets stabilising atmospheric greenhouse gas concentrations this century, IAMs suggest initially modest emission-limiting actions [10]. For example, Nordhaus (2007) suggests an optimal emissions reduction of 14% in 2050 versus "business-as-usual". However, IAM results indicate significant global warming impacts on people, property, wildlife and ecosystems (Weyant, 2017), although not considering individual companies' exposures.

Stern *et al.* (2022) believe IAM methodologies are flawed, inadequately covering catastrophic climate risks. They note contradiction between the international community consensus [11] and a major position in economics. The international community consensus being to limit warming, accepting structural economic changes, carbon pricing, regulations and other measures. Against this, Stern *et al.* (2022) note a particular major stream of thought within the economics profession, largely based on IAMs' results, suggests, controversially, a cost-benefit optimum of over 3°C warming in 2100; an outcome deemed catastrophic by climate scientists. Exploring this contradiction, Stern *et al.* (2022) conclude IAMs have gone astray, seeing serious shortcomings in methodologies pertaining to climate change's immense risks. Incorporating even limited catastrophic consequences via more severe damage functions, or different assumptions on technology or distribution, generates markedly different results. Thus, IAMs' "optimal" trajectories and cost of carbon are extraordinarily sensitive to precise model specification, with plausible alternative specifications generating results much closer to the international consensus. They conclude this sensitivity makes IAMs' guidance of very limited value for either intensity of action or policy determination [12]. Apart from policy guidance unreliability, being macro-economic models, IAMs do not provide individual company estimates of potential climate-related damages associated with their emissions. Restricting companies' capacity to freely emit and externalise climate damages addresses Stern *et al.*'s (2022) concerns about market failure, helping financial markets better price emissions, which are often underpriced (Calvet *et al.*, 2022; Campiglio *et al.*, 2023).

2.3 Climate litigation

Climate litigation potentially exposes high-emitting firms to punitive damages, increasing liquidity and bond default risks (Capasso *et al.*, 2020; Sato *et al.*, 2024). Setzer and Higham (2022) note that over 70% of the 2,002 climate litigation cases filed have been before US courts with the majority of cases filed by non-governmental organisations or individuals. Outside the United States, national or subnational governments are the most common climate case defendants, for example, challenging failure to legislate sufficiently ambitious emissions reduction pathways. However, Setzer and Higham (2022) also report shifts towards high-emitting companies as defendants, typically for US cases, and more recently elsewhere. Sato *et al.* (2024) observe that annual climate litigation filings grew to more than 200 in 2021, with 18% of these against individual firms. Cases targeting companies typically aim to change governance and decision-making to disincentivise emissions, or seek damages for climate impacts based on emissions, potentially impacting profit-margins, challenging major emitters' business models and damaging reputation (Setzer and Higham, 2022).

A growing development is "strategic" climate litigation where claimants look beyond individual litigant concerns to advance climate policies, raise public awareness or change government or industry actors' behaviour (Batros and Khan, 2020). Sato *et al.* (2024) suggest that investors' awareness of climate litigation risk is increasing, with consequences including legal fees, fines, penalties, higher insurance costs and decreased financial leverage. Meanwhile, central banks, regulators, insurers and investors are seeking to more comprehensively assess companies' climate-related risks [13]. Their results indicate that case filings led to abnormal decreases in target stock prices by 0.35%, with a larger −0.99% effect from negative court decisions. For the largest emitters in sectors such as energy, they also report a statistically significant decrease in stock prices of 0.57% on case filings and negative decisions, amplifying to −1.50% for negative decisions alone. These results highlight that investors need to be able to estimate potential emissions-related climate damages, including from EW events.

2.4 Valuation response

Ilhan *et al.* (2021) find that options markets reflect climate policy uncertainties with strong evidence that downside protection is more expensive for higher carbon-intensity S&P500 sectors. They conclude the market's perception of a firm's climate policy exposure is driven by its industry affiliation. Like Bolton and Kacperczyk (2021, 2023), they use quantitative statistical methods to establish the qualitative result that higher emissions are associated with higher option costs. However, these studies do not attempt to estimate the appropriate size of market response for quantified emissions, with Ilhan *et al.* (2021) concluding that market response is based on industry affiliation, but not directly on emissions. This is consistent with the view that investors appreciate that pricing should reflect emissions, but not by how much, and rather than emissions, heuristically using industry affiliation. Overall, investors demand higher climate risk premia for high-emission companies (Bolton and Kacperczyk, 2021, 2023; Sautner *et al.*, 2023).

As discussed above, litigation against the largest energy sector emitters has resulted in 1.50% stock price falls following negative judgements (Sato *et al.*, 2024). Bolton and Kacperczyk (2021, 2023) find reduced valuations for firms with higher emissions, although not carbon intensity (emissions over sales, assets, or kWh). Also, that carbon premium materialised between 1990 and 2017, increasing with tighter policies, appearing consistent with Ilhan *et al.* (2021). Thus, investors discount high-emitting firms more, seeking higher compensation (a carbon premium) for holding stocks of high CO_2-emitting firms. Across different scopes of emissions, Bolton and Kacperczyk (2021) find that a one-standard-deviation increase in emissions increases the carbon premium by up to 4% annually. In addition, In *et al.* (2019) show that a portfolio long low-emission companies and short high-emission companies generated abnormal positive returns between 3.4% and 5.4% annually between 2005 and 2018 (although not from the high-emitters' under-performance). Unlike the litigation examples, these stock price adjustments appear to have emerged gradually, rather than rapidly, in response to an external event.

However, whether adjustment magnitudes are correct is unclear. This includes adjustments while emissions-related damaging climate events occur (such as extreme weather events), which may allow better quantification of relevant damages (our study's focus). Stern *et al.* (2022) believe climate risks are very far from being fully priced into markets. A conclusion corroborated by Bolton and Kacperczyk (2023, p. 3682) who suggest that " … *a difficult question to answer is how changes in carbon* … *risk get impounded into asset price*" and Condon (2022, p. 66) who argues that "*there is* . . . *ample reason to believe* . . . *equity analysts "are systematically less able to assess* … *valuation implications" of climate risks*". In this article, we aim to solve this issue by using established methods from the climate sciences to quantitatively estimate appropriate market responses to EW events for individual companies based on their emissions.

3. Methodology

By analysing climate attribution literature, we build a conceptual/theoretical model linking corporate emissions to extreme weather damages. We consider three possibilities: EW events as (1) isolated, (2) recurring at constant frequency or (3) at growing frequency. Scientific evidence supports EW events recurring at growing frequency. Making straightforward assumptions, we express our model parsimoniously as a Gordon's Growth variant, illustrated with a hypothetical case study. Our model development is interdisciplinary, bringing physical sciences results into the economic/financial domain. It helps bypass key challenges such as interdisciplinary differences in approach, interpretation and communication [14]. Evidence supporting our model includes aspects from established physical sciences results.

Regarding empirical evidence supporting our model, studies conclude that climate risks are not fully priced into markets even for current emissions (Bolton and Kacperczyk, 2021, 2023; Condon, 2022; Stern *et al.*, 2022). Thus, even less likely so, for historically aggregated cumulative emissions, as we propose. This makes empirical validation of our theoretical approach challenging, although not impossible. Nonetheless, we find circumstantial evidence consistent with our model from studies based on emissions and climate litigation. We include sensitivity studies to explore key model inputs. Consequently, our model should be seen as demonstrating feasibility, providing estimates and offering insights, as we discuss below. We would expect future research efforts to concentrate more on the empirical aspects of our conceptual proposition.

4. Development of theoretical framework

We consider significant EW event damages (Table 1, D_E). 2017 North Atlantic hurricanes caused \$265bln US mainland damages and 2021 natural disaster damages exceeded \$300bln (National Hurricane Center, 2018; Wagner, 2022). Full damages may be multiples of direct effects (Brown, 2023). Scientific climate attribution causally links emissions to EW damages through three steps. Firstly, firms' activities emit greenhouse gases; that secondly, cause GW; which thirdly, is linked to extreme weather by probabilistic attribution statements. The predominant greenhouse gas is carbon dioxide; lithospheric carbon returns underground naturally over exceedingly long geological timescales, so once burned, it effectively accumulates permanently in the atmosphere (Allen, 2016; IPCC, 2021). Hence, cumulative (not current) emissions are the appropriate GW metric. Fossil fuel industry products account for ~70% of all anthropogenic emissions. Between 1751 and 2017, nine companies generated 14.5% of emissions (Griffin, 2017; Heede, 2019), including emitters operating in the energy sector.

Probabilistic attribution statements allow some event probabilities' GW-generated increases to be quantified (Otto *et al.*, 2018a; Philip *et al.*, 2020). Climate is statistically "possible weather" (Allen, 2003). Global warming alters weather patterns and statistical distributions, raising probabilities of events including strong winds, intense rainfall (or drought), or high temperatures, thus increasing EW events' likelihoods (Harrington and Otto, 2018). The fraction of attributable risk (FAR) quantifies probabilities from computer simulations and historical data, evaluating GW-generated extreme weather event risk proportion (Allen, 2016; Otto, 2017), mirroring financial options. Suppose an EW event's (perhaps a damaging hurricane) average return period decreased from 1-in-99 years ($R_k = 99\,years$) in pre-industrial times (denoted t_k) to 1-in-33 years today (t_0; $R_0 = 33\,years$). Annual probabilities are reciprocals of return periods, $p_k = 1/R_k$ and $p_0 = 1/R_0$. Event probability increased threefold versus pre-industrial times; two-thirds of the risk is GW-generated. Following Allen (2003) and Harrington and Otto (2018):

$$FAR(t_0) = F_0 = \frac{R_k - R_0}{R_k} = \frac{p_0 - p_k}{p_0} \tag{1}$$

We analyse real-world EW events (such as in Table 1) to explore historical damages' attribution. This considers the evolving climate response to human emissions. For Table 1's extreme weather events, discrete events (including cyclones) best suit the FAR analysis, where damages must be "all-or-nothing". Continuum phenomena (e.g. drought or flood levels) must be treated differently (Brown, 2023), although infrastructural breaking points impart "all-or-nothing" aspects. For example, if flood defences are overtopped, or water supplies exhausted. For our event analysis in Table 1, we assume FAR is appropriate.

Our framework demands PV (present value) estimation of future EW liabilities, requiring a climate liability discount rate, *r*. Extended periods make determining climate liability discount rates difficult (Ackerman *et al.*, 2009; Stern, 2006). Discounting diminishes distant future costs and PVs can be extremely rate sensitive (Gollier and Weitzman, 2010). Climate rates should be below "conventional" rates and decrease, raising PV's of distant future costs relative to constant rate discounting (Weitzman, 1994). Gollier and Hammitt (2014) recommend 4%–1% rates for immediate maturities to the indefinite future. Lemoine's (2020) work on climate risk premiums shows uncertainty about warming damages, and how they reduce consumption, increase the social cost of carbon, and decrease the discount rate. Lemoine's results include a near-term 3% annual rate falling to around 1% for cash flows in 500 years. Literature reveals conflicting views. Firstly, certain studies, like those Stern *et al.* (2022) mention, considering intergenerational equity, argue $r > 0$ is unethical as implying future lives are worth less than current lives. Secondly, the descriptive (market) view is that climate-related investment rates must be competitive (Stern, 2006; Weyant, 2017). Our conceptual model prioritises insights using Gordon's variant modelling approach, adopting a conservative discount rate as discussed below.

Returning to physical climate insights, following Allen (2003, 2016), even if all emissions (anthropogenic and natural) immediately ceased, and ignoring climate feedback, current climate and event probabilities would persist. Thus, weather patterns and statistical distributions (such as for rainfall volumes and temperatures) altered by present GW, resulting in increased extreme weather event likelihoods, will continue. Hence, EW events cannot be considered isolated, but now recur with increased annual probability. Further, scientific evidence (see Appendix 1) points to ongoing increases in EW event frequencies. Carbon dioxide (the predominant greenhouse gas) is extremely long-lived in the atmosphere. Carbon only naturally returns to the lithosphere over geological timescales, so once burned, carbon dioxide effectively accumulates permanently in the atmosphere (Allen, 2016; IPCC, 2021). We thus develop a liability model that treats EW events as perpetual with growing annual probability and expected annual liability.

4.1 Gordon's variant model and climate discount rates

Table 2 gives our model's requirements, while Figure 1 outlines our framework for firm EW liability calculation ($L_{i,0}^{EW}$) for the examples summarised in Table 1. We use discount rate $r = 4\%$ (literature supports $1\% \leq r \leq 4\%$). We recommend climate attribution studies include relevant dates, FAR, return periods and associated uncertainties.

We parsimoniously and tractably model EW liabilities using a Gordon's (1963) variant model, as frequently used in equity valuation. Instead of dividends, we model firms' EW liabilities ($L_{i,0}^{EW}$):

Table 2. Model requirements, sources and comments

Requirements	Description	Sources	Comments
D_E	Event damages	Insurers, government agencies, EM-DAT, n.d..	Media reports may provide immediate damage estimates
I	Inflation data	Central banks, World Bank	For analyses immediately following a discrete event, inflation adjustment is unnecessary ($I = 1$)
η_i	Historical company emissions proportion	Heede (2019) and similar emissions databases	Characteristic of company analysed. Likely changes slowly for individual firms
Ψ_i	Firm's responsibility share	We use $\Psi_i \approx 0.4$ (see main text)	Depends on societal willingness or ability to enforce damages. Offers significant scope for analyst judgment
R_0 or p_0	Return period or annual event probability	Climate analyses following EW events	Related to FAR. Analysts can potentially estimate from similar events (see Table 1)
F_E	Fraction of Attributable Risk (FAR)	Climate analyses following EW events	Attribution studies may be published in months following events. Initially, analysts could estimate provisional FAR values from similar events (see Table 1)
t_0	Date of EW event	Public media	Typically, the year of the event
t_k	Earlier date	Climate analyses following EW events	Figure A2 suggests typically no earlier than 1965
r	Climate discount rate	Literature suggests $1\% \leq r \leq 4\%$ (see main text). We use $r = 4\%$	Offers significant scope for analyst judgment

Source(s): The authors

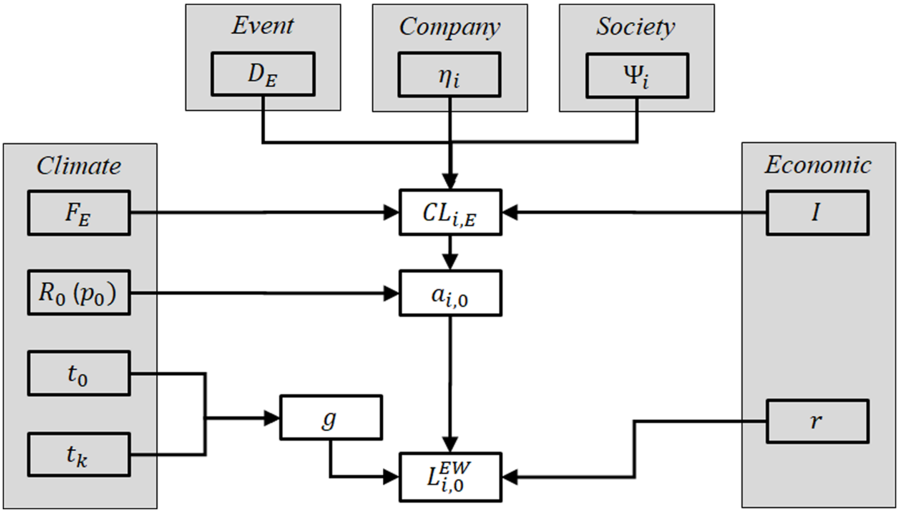

Figure 1. Valuation framework showing how model inputs contribute to firm EW liability ($L^{EW}_{i,0}$). Source: The authors

$$L_{i,0}^{EW} = \frac{a_{i,0}(1+g)}{r-g} \qquad (2)$$

where $a_{i,0}$ is company i's annualised EW liability at $t = 0$, g is liability growth rate, and r is climate liability-related annual discount rate. For simplicity, we assume constant g. We estimate defensible and conservative values for $a_{i,0}$, g and r. Although appearing challenging, we base these on climate and economic research.

We require climate liabilities' discount rates, which, as indicated in the previous section, is an extensive topic, potentially addressable through stochastic modelling. We do not further investigate this aspect, as we prioritise conceptual insights using Gordon's variant modelling approach. We reveal crucial interactions between r, g, and the changing climate's potentially perpetual liabilities. For example, if climate liabilities grow at, or faster, than discount rates ($g \geq r$), so that expected climate damages grow faster than discount rates, their PV ($L_{i,0}^{EW}$) becomes infinite. If GW intensifies rapidly, this highlights the challenges of uncontrolled global warming's major financial consequences. Literature suggests annual discount rates between 1% and 4%, declining towards a distant future 1% (Gollier and Hammitt, 2014). Many economists adopt 3%, despite arguments for lower rates (Stern *et al.*, 2022). As constant rates yield lower PVs than declining rates, for parsimony, tractability and to be conservative, we select constant r as the high range of the above (1%–4%), namely 4%.

4.2 Extreme-weather liabilities and company attribution

We consider EW, including hurricanes, extratropical cyclones, heatwaves, precipitation, flooding and droughts (IPCC, 2021; NASEM, 2016). Following Brown (2023), we require events to be discrete (impactless without an "event"), equivalent to Frame *et al.*'s (2020) step-change damage functions, limiting the event types we can consider. Our analysis of climate events in Table 1 is subject to this caveat. Brown (2023) notes that for climate events on a continuum, a different approach is required. Frame *et al.* (2020) and Lott *et al.* (2021) examine liabilities for national economies or individuals; we consider individual companies. Allen (2003) estimates liabilities using FAR (F_E) and event damages (D_E), as $D_E F_E$. Rayer *et al.* (2023) consider companies including inflation (I), cumulative emissions (η_i) and emissions responsibility (Ψ_i):

$$CL_{i,E} = D_E F_E I \eta_i \Psi_i \qquad (3)$$

$CL_{i,E}$ is company i's liability for EW event, E (in US$-values), I inflation-adjusts to the analysis year (e.g. a 2017 event analysed in 2022 dollar-values). Extended events (e.g. Table 1's 2015–2017 South African drought), must have damages expressed at a single time. Thus, $I = (1+\pi_1) \times \ldots \times (1+\pi_n)$, with sub-period inflation rates $\pi_1, \ldots, \pi_n$. Firm i's total anthropogenic cumulative emissions' proportion is η_i $(0 < \eta_i < 1)$. Following prior literature (Allen, 2016; Otto *et al.*, 2017; Lott *et al.*, 2021), we base economic damages on cumulative emissions. η_i is straightforwardly interpretable as the fraction of the totality of all human emissions accumulated over historical periods to the present. Thus, following these authors, 100% of human cumulative emissions to date result in 100% of (anthropogenic) global warming [15].

Rayer *et al.* (2021, 2023) consider responsibility share, Ψ_i $(0 \leq \Psi_i \leq 1)$, reducing corporate liability estimates. Following Mittiga (2019) this requires a moral decision. Should companies bear full emissions responsibility ("polluter pays", $\Psi_i = 1$) or should others, i.e. their customers, individuals or wider society, bear it ("beneficiary pays", $\Psi_i = 0$)? We extend, to encompass moral (m) and societal (s) considerations, with $\Psi_i = \psi_{i,m}\psi_{i,s}$ (where $0 \leq \psi_{i,m} \leq 1$ and $0 \leq \psi_{i,s} \leq 1$). Shue (2017) discusses users' and producers' relative abilities to influence change, and high-emitting firms' awareness of climate damages and engagement in "climate denial”. However, society can prevent firms from externalising emissions costs using the mechanisms of climate litigation, regulation, carbon taxation, credits or social licence (Chameides and Oppenheimer, 2007; Griffin, 2020; Setzer and Higham, 2022). Alternatively, governments may accept responsibility for citizens’ harmful emissions. Society may consider producers morally responsible ($\psi_{i,m} = 1$) yet be unwilling or unable to enforce damages ($\psi_{i,s} = 0$), in which case, $\Psi_i = 0$. Consistently, Sato *et al.* (2024) find emitter share prices decline following climate litigation case filings, and further on receiving adverse judgements, both providing evidence that $\psi_{i,s} > 0$. Ilhan *et al.* (2021) find high-emitting firms’ protection costs increase when public climate concerns rise, supporting $\psi_{i,s}$’s relevance to pro-climate policy likelihood. Plausibly $\psi_{i,m} > 0$ and $\psi_{i,s} > 0$. The moral arguments look compelling and societal mechanisms addressing emissions are developing or under litigation. We take the mid-value of Rayer *et al.*’s (2021) corporate responsibility shares of 0.77 and 0.885 as potentially reflecting ψ_m. Agnostically, we adopt $\psi_s = 0.5$, making $\Psi_i \approx 0.4$, implying firms are responsible for 40% of the damages from their emissions.

Overall, our formulation for corporate liability estimates, $CL_{i,E}$, appears well supported by literature. We may thus estimate $a_{i,0}$ in our Gordon’s variant model. Events reoccurring with average return period R_0 cause $CL_{i,E}$, giving current expected annual liability $a_{i,0} = CL_{i,E}/R_0 = CL_{i,E}p_0$. This appears uncontentious, given FAR’s probabilistic attribution, with literature supporting average return periods. We extend previous approaches by considering PVs of expected climate damages from accumulated emissions. However, with further temperature increases, greater EW frequency and damage are expected.

4.3 Extreme-weather liability growth

Evidence indicates increasing EW frequency and intensity with warming, potentially amplified by local atmospheric feedbacks, greater humidity, circulation changes and extreme wind (Masson-Delmotte and Zhai, 2022). Even with net zero emissions, climate feedback, including snow and ice reductions (promoting warming by lessening solar energy reflection back to space), and natural warming processes, may intensify GW (Goodwin, 2018). Warming is increasing around 0.2 °C per decade and possibly accelerating (Haustein *et al.*, 2017).

Attribution compares pre-GW and present times, covering historical intensification, allowing growth rate estimation for our model from event probability changes between early and present times to be algebraically illustrated (see Appendix 2) as follows:

$$g \approx \frac{1}{a_{i.0}} \frac{da_{i,0}}{dt} = \frac{1}{t_0 - \max(t_k, 1965)} \tag{4}$$

As used in Table 1, for the 2017 North Atlantic hurricane season, taking $t_k = 1980$ and $t_0 = 2017$, we have $g \approx 2.7\%$. As policy responses likely underestimate (or neglect) GW intensification, our approach appears superior to treating extreme weather events as “one-off” or repeating at constant frequency. Appendix 2’s linear assumption appears capable of falsification as new results become available. Stern *et al.* (2022) argue that constant growth will likely underestimate GW intensification, and recent research suggests possible acceleration (Curran and Curran, 2025). Contributors include emissions rates and natural processes, reinforcing global warming if climate “tipping points” are passed. Growth rates are expected to vary between different EW events and types; thus, hurricane and drought damages can grow at different rates.

5. Estimating companies’ potential liabilities for a hypothetical case study

We illustrate our model, applying 2017 North Atlantic hurricane season data to a representative hypothetical high-emission company based on the data presented in Table 3. Before exploring GW intensification, we consider events firstly, as isolated, and secondly,

Table 3. Hypothetical Company "H" profile

Description	Parameter	Value
Proportion of total anthropogenic cumulative emissions	η_H	1.5%
Emissions responsibility share	Ψ_H	0.4
Market capitalisation	V_H	$200bln

Note(s): This table contains data of a hypothetical company that we use for the estimation of potential climate liabilities

repeating at current rates. The second case treats EW damages as a constant expected annual liability, supposing GW alters statistical weather distributions, which develop no further (e.g. using Table 1, an event like hurricane "Harvey", becomes about 6 times more likely, but that is all). Finally, we explore implications for intensifying GW. Thus, our example considers three cases, i.e. a single liability, a flat perpetuity, and a growing perpetuity.

5.1 Isolated and constant frequency events

As one-off events, we compare our hypothetical company $CL_{H,E}$ against its market capitalisation, V_H. The 2017 North Atlantic hurricane season damages were $D_E = \$265\ bn$, neglecting inflation adjustment ($I = 1$). Applied to Table 3's hypothetical company with FAR from Table 1 we have $CL_{H,E} = \$265\text{bn}\times 0.84\times(1.5/100)\times 0.4 = \$1.34\text{bn}$, or $CL_{H,E}/V_H = 0.7\%$ of market capitalisation. Absent share issuance or redemption, this can be interpreted as a share price revaluation.

As GW will likely continue indefinitely, consider the PV of $a_{i,0}$, in perpetuity, $a_{i,0}/r$, reflecting expected liabilities without further global warming increases. Continuing our example, with a return period of 16 years, $a_{H,0} = CL_{H,E}/R_0 = \$1.34\text{bn}/16 = \$0.083\text{bn}$. At $r = 4\%$, the PV is $[a_{H,0}/r]_E = \$2.1\text{bn}$, or $[a_{H,0}/r]_E/V_H = \$2.1\text{bn}/\$200\text{bn} = 1.0\%$ of market capitalisation. However, as evidence supports intensifying GW, we proceed with a more accurate estimation of potential climate liabilities for the same firm.

5.2 Global warming intensification

We now include GW intensification. We apply our model (Eq.2) to Table 3's hypothetical company and the 2017 North Atlantic hurricane season. With $r = 0.04$, $g = 0.027$ and $a_{H,0} = \$0.083\text{bn}$ the event liability is

$$L_{H,0}^{EW} = \frac{\$0.083\text{bn}\times(1+0.027)}{0.04-0.027} = \$6.6\text{bn}$$

or $L_{H,0}^{EW}/V_H = \$6.6\text{bn}/\$200\text{bn} = 3.3\%$ of market capitalisation, significantly increased by expected $a_{H,0}$ growth. Although potentially lower than market rates, $r = 4\%$ reflects the literature discussed earlier in the article. This covers one extreme weather type (hurricanes) and geographical locality (the North Atlantic), implying significant potential liability for high-emitting firms. While simplified, our model highlights severe economic consequences from rapid GW event damage growth for risk premia and corporate values.

6. Discussion

Having developed a Gordon's variant model for EW event liabilities, we now appraise our model, including its assumptions, supporting evidence in the literature, sensitivities and requirements.

6.1 Model assumptions

Whether our Gordon's variant model's assumptions are robust, or conservative, is crucial. We summarise key assumptions in Table 4 implicitly indicating our model's limitations. Long-term cashflow analyses are extremely sensitive to discount rates. Prior research recommends rates from 1% to 4%. We use a constant (rather than declining) rate of $r = 4\%$, lower than costs of capital, but relatively high for climate analyses, making it a conservative estimation (Damodaran, 2024; Stern *et al.*, 2022). We assume event probabilities grow linearly. Climate "tipping points" amplifying global warming intensification appear plausible, with constant growth rates likely an underestimate (Stern *et al.*, 2022) and possible evidence of acceleration (Curran and Curran, 2025). Appendix 1's climate data supports linear event probability increases over a limited warming range, although faster increases appear possible. Constant expected annual liability growth appears scientifically well-supported and conservative.

What about our model's overall form? We use growth and discount rates within a Gordon's variant model, including perpetually occurring, and growing, climate liabilities. Regarding perpetual liabilities, carbon dioxide from the combustion of underground carbon deposits only returns to the lithosphere over geological timescales (more than 10,000 years or so). Therefore, it effectively accumulates in the atmosphere, permanently changing climate and EW event probabilities (Allen, 2016; IPCC, 2021). Thus, including perpetual liabilities in our model is robustly supported by climate science. Is it reasonable that such liabilities should be growing?

Table 4. Key model assumptions

Assumption	Comments
Gordon's variant model structure	Model assumptions parallel those of Gordon's growth model, namely constant $a_{i,0}$, r and g. We discuss these and other assumptions below
Constant $a_{i,0}$	Defined commencing with Eq. (3) with growth assumed via event increased annual probability (or potentially intensity). Thus $D_E I \eta_i \Psi_i$ assumed constant. Annual liabilities increase by g
Constant g	Event probabilities are assumed to grow linearly with time based on extrapolation of historical climate data, allowing estimation of growth rate applicable to $a_{i,0}$ in perpetuity (see main text for discussion of climate feedbacks). Appendix 2 assumes constant $D_E I \Psi_i$ and negligible changes in η_i. Constant $D_E I$ assumes constant event damages in inflation-adjusted terms
Constant r	For tractability, our model assumes constant climate discount rate, which also makes damage estimates conservative. Literature also supports declining discount rates and stochastic modelling may be appropriate (see Section 4)
Constant η_i	We assume that a firm's accumulated emissions, as a proportion of all human emissions, remain constant in perpetuity, making this a "business as usual" estimate. For example, a high-emitting firm ceasing to exist in 50 years' time would have zero (current) emissions after that date. However, if the firm's existence ceased because it was acquired by another organisation, the acquirer would take on those emissions and liabilities
Constant Ψ_i	We assume a consistent societal position regarding emitters' responsibility (see Section 6.1 for further comments)
FAR	We assume FAR analysis is appropriate for the extreme weather events considered, implying step-change damage functions (see sections 4 and 4.2)
GWP100	While carbon dioxide is the primary greenhouse gas, the climate impact of other gases is assessed using metrics such as GWP100 (Shine *et al.*, 2005). We assume widely accepted metrics, such as GWP100, are appropriate for conversion between different gases' climate impacts
Event probability	We assume EW event damages increase due to increased annual event probability. This neglects increases in event intensity. However, should annual event probabilities exceed unity, we assume that expected annual liabilities continue to grow at the same rate due to increased event intensity, or multiple events annually

Source(s): The authors

Scientific evidence shows ongoing increases in EW event frequencies associated with long-term historical trends of rising warming (Appendix 1) and warming appears to be increasing (Haustein *et al.*, 2017). What about future trends? Even if all anthropogenic and natural emissions ceased and with no climate feedback, current warming levels would not be expected to reduce (Allen, 2003, 2016). Thus, even if humanity robustly implemented global net-zero emissions, at best, warming (and EW event probabilities) would remain at current levels, but not reduce. Even so, climate feedback, including snow and ice reductions and natural warming processes, may intensify global warming (Goodwin, 2018). We assume linear event probability increase with temperature (Figure A1) and linear temperature increase with time (Figure A2) to estimate future growth. Our modelling framework thus neglects non-linear probability and temperature increases when estimating growth rates (for details, see Appendix 2). Curran and Curran (2025) suggest possible warming acceleration, while Figure A1 potentially indicates above linear event probability increases at higher temperatures. We thus, may be underestimating future event probabilities and damages [16].

What about the climate liability growth rate reducing in the future, perhaps in response to policy or other measures? However, Figure A2 in Appendix 1 includes data after 2015, which to date shows no gradient reduction despite the Paris Agreement. Although the policy landscape might have appeared sympathetic to the rapid adoption of decarbonisation measures before January 2025, the new US administration's arrival makes it appear less so. Significant emissions appear likely to continue, for a period, at least [17]. Overall, a rapid reduction in emissions, warming and hence event growth rate appears optimistic. Thus, following Stern *et al.* (2022), constant growth rates appear likely to be an underestimate, with possible evidence of acceleration (Curran and Curran, 2025). Although an approximation, it thus appears reasonable (and perhaps conservative) to treat EW event liabilities as perpetual and with a constant annual growth rate.

Event return periods and FAR are well-established (see development of the theoretical framework). However, FAR applicability is limited to discrete events, thus may be unsuitable for gradual impacts such as floods and droughts (Brown, 2023), although events overwhelming infrastructure (e.g. flood defences, water supplies) can impart "all or nothing" aspects. Unfortunately, analyses often omit FAR or return period uncertainties or may state "*at least*" some probability multiple (see, e.g. Frame *et al.*, 2020). Including uncertainties strengthens application. Basing liabilities on greenhouse gas emissions proportion (η_i) appears scientifically sound. Cumulative emissions neglect shorter-lived greenhouse gases' natural decay. Often accompanying CO2 emissions, non-CO2 emissions (e.g. methane), promote warming, helping trigger climate feedback, being typically assessed using the GWP100 metric, incorporating some shorter-lived greenhouse gases' decay (Shine *et al.*, 2005). Hence, constructing η_i on accumulated emissions using an appropriate metric appears reasonable. For simplicity, we assume that individual firms emit perpetually, although future emissions may reduce, lessening Eq. (2)'s liability $L_{i,0}^{EW}$ by appropriate annual amounts. However, slight reductions will only modestly effect η_i (which depends on cumulative emissions) and future reductions must be discounted to present values, lessening changes to our liability estimate.

Emissions responsibility offers judgemental scope. Total customer responsibility ($\Psi_i = 0$) appears implausible for many products' emissions (e.g. fossil fuels). Often, alternatives are unavailable, or much more expensive. Moral considerations inform societal debates, including awareness, "climate denial", and resource imbalances to address harms between companies and users (often private individuals). We use $\Psi_H = 0.4$ (firm responsible for 40% of damages), lower than Rayer *et al.*'s (2021) 0.77 or 0.885 (which we interpret as ψ_m). Thus, under reasonable assumptions, our responsibility apportionment appears conservative. Uncertainties include those associated with discount rate, FAR, R_0, emissions data (η_i) and responsibility (Ψ_i). Analyses often omit uncertainties in FAR, R_0, and η_i. Discount rate selection and emissions responsibility require analysts' judgement, both are assumed constant. As societal positions on emitter responsibility may evolve, these are currently unknown; so, we assume these are constant. Literature also supports declining discount rates (or stochastic modelling). Along with other assumptions mentioned in Table 4 and the above uncertainties, these may best be addressed by sensitivity studies. Overall, our model is well-supported by the literature.

6.2 Supporting evidence

An important question is whether economic and financial studies provide supporting company emissions revaluation evidence. Bolton and Kacperczyk (2021, 2023) find higher company carbon premiums (reduced valuations) for higher, or growing current emissions, but not carbon intensity (emissions over sales, assets or kWh). They find emissions levels are persistent, although neglecting cumulative emissions, which is of utmost importance as we discussed earlier. If persistence implies current emissions are a cumulative emissions proxy and increasing emissions are a proxy for higher future emissions, this is consistent with our model. As carbon intensity differs from cumulative emissions, Bolton and Kacperczyk's (2021, 2023) finding that there is no carbon intensity premium is also consistent with our model.

Carbon premium materialised between 1990 and 2017 and increased with tighter policies. Regulations are expected to target high-emitting firms (Bolton and Kacperczyk, 2021, 2023). Ilhan *et al.* (2021) find that climate risk premiums increase with societal awareness in options markets. These support $\psi_{i,s}$ (whether society is willing and able to enforce damages) as evolving and dependant on firms' emissions levels. Quantitatively, Bolton and Kacperczyk (2021) find a 4% higher emitting firms' carbon premium, while In *et al.* (2019) find relative underperformance by high-emission companies between 2005–2018 of 3.4%–5.4% annually. Our representative examples are of a similar order of magnitude, totalling 6% (see Table 1), although we consider specific extreme weather events, and the above studies assess market response in principle to all emissions-related GW consequences.

Climate litigation affects major emitters, with targets' stock prices falling -0.6% on case filings, and -1.5% following unfavourable judgements (Sato *et al.*, 2024). Cases vary, often unrelated to EW, but better mimic individual event damages than aggregate market response. Quantitatively, Sato *et al.*'s (2024) results are of a similar magnitude to Table 1 (0.002%–3%) and consistent with $\psi_{i,s}$. A low $\psi_{i,s}$ increases upon case filing and again following an unfavourable outcome, consistent with increasing societal enforcement of damages. Post-2019 climate litigation responses are greater (Sato *et al.*, 2024), consistent with higher $\psi_{i,s}$, or events' greater frequency or damages. Thus, circumstantial company revaluation evidence is consistent with our model. This likely reflects evolving climate liability estimation, e.g. 2017 for carbon premium appearance and uncertainty on impounding carbon-risk into asset prices (Bolton and Kacperczyk, 2021, 2023).

6.3 Sensitivity to growth rate and emissions responsibility

We explore the sensitivities of our model to plausible changes in growth rate g and emissions responsibility share Ψ_i. Growth rates are estimated from the interval between pre-GW and present dates (Eq.4). Following Appendix 1, the pre-GW date is taken as no earlier than 1965, as Figure A2 shows a temperature inflection point around 1965 with a higher warming gradient thereafter. However, the data is interpretable as including earlier inflection points (e.g. 1910s monthly observations), although with a lesser gradient. Thus, potentially, the pre-GW date could be significantly before 1965, implying lower growth rates. Not all events are affected, as, for example, the 2017 North Atlantic hurricane season analysis commences from 1980, avoiding the 1965 cut-off. From Table 1, the event with the largest liability and potential pre-1965 earlier date is the 2023 US heat dome. In this case, the growth rate would reduce from $1/(2023-1965) = 1.7\%$ to $1/(2023-1910) = 0.9\%$, decreasing the estimated liability from \$1.4bn to \$0.98bn or 0.5% of the hypothetical company market capitalisation.

Responsibility share appears dependent on societal considerations. We adopt $\Psi_i \approx 0.4$ throughout our analysis. Ψ_i is a linear factor of $a_{i,0}$ (Eq.3). Thus, doubling or halving Ψ_i, the proportion of damages a firm is responsible for, doubles or halves the estimated event liability. Increasing the responsibility share to 0.77 or 0.885 as suggested in prior literature (Rayer *et al.*, 2021) increases estimated event liability in the same proportions, 0.77/0.4 or 0.885/0.4. Conceptually, these sensitivities make sense. If an EW event type has only developed since 1980, then considering dates earlier than 1965 will not affect growth estimates. Only the analysis of event types that amplified gradually over longer periods would be modified. By comparison, while responsibility share may reflect "polluter" versus "beneficiary pays" debates, the sharing of costs is, in principle, a direct societal decision, so proportional liability apportionment appears expected.

Figure 2 extends our 2023 US heat dome sensitivity study. Exploring climate liability discount rate r between 1%-4%, for the \$1.4bn liability ($L_{H,o}^{EW}$ in Table 1) to remain constant, we could either adjust the responsibility share (Ψ) or the implied earlier date (t_k). For low r, responsibility share and t_k struggle to adjust to maintain constant liability. Lower responsibility share and earlier t_k (implying a lower climate liability growth rate) allow smaller discount rates in our model. This is expected as lower r increases PVs. For liability to be unchanged, a lesser responsibility share must be ascribed or a lower growth rate. As above, responsibility share sensitivity is proportionate, reflecting our model's linear dependence. Figure 2 explores t_k dates before 1965. Reducing g to compensate for lower discount rate, implies earlier t_k (pre-GW date). Figure 2 shows dates as early as 1600. However from Figure A2 of the Appendix, we can see that GW started around 1880–1900 or so. Thus, ascribing earlier dates to t_k appears implausible. Based on Figure 2 for liabilities like those in Tables 1 and it would appear that climate liability discount rates of around 3%–4% appear best supported by our model.

7. Conclusion

Our Gordon's variant model provides an accessible method to estimate corporate historical emissions liabilities for EW damages. A key insight is that emissions generate perpetual, and likely increasing, climate-related extreme weather event damages. Estimating EW damages' growth rates illuminates challenges of economic growth (accompanied by emissions) outstripping associated climate damages. We illustrate our model for a hypothetical high-

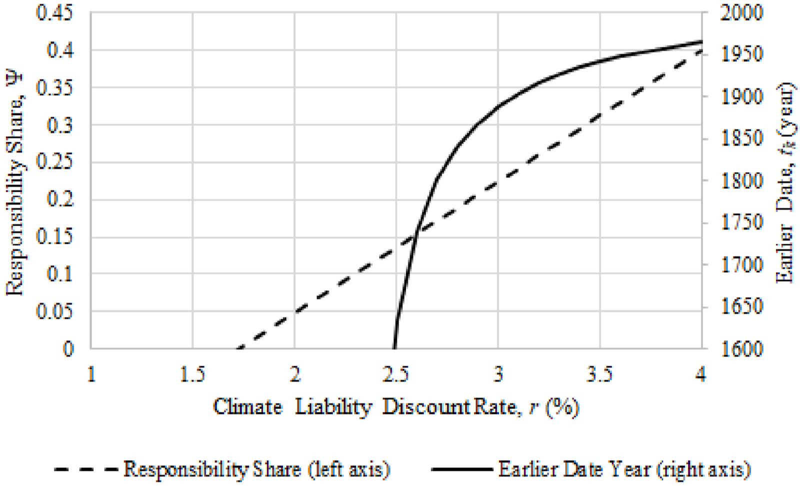

Figure 2. Sensitivity study for responsibility share (Ψ) and earlier date (t_k). Source: Estimated by the authors

emitting company, indicating potential liabilities from the 2017 North Atlantic hurricane season are significant, perhaps around 3% of market capitalisation.

In practice, our model helps company analysts, accountants, equity and bond investors, lenders, insurers, regulators and litigation parties. Analysts can compare projected returns on current and proposed activities, and associated emissions, with estimated event liabilities. This informs equity investors, bond investors and ratings agencies, and bank lending risks. For equities, we help answer Bolton and Kacperczyk's (2023) and Condon's (2022) concerns that analysts are less able to assess climate risks' valuation implications. Analysts can estimate share price revaluations following EW events, as damages are reported. Our model helps accountants assess emissions in relation to identifying and managing climate risks for disclosure in company annual reports, under regimes such as TCFD/ IFRS. However, our modelling approach is approximate, and market practitioners will also consider other corporate valuation factors. One suggestion would be for our model to contribute to investment accounting liability ratios. For example, as an additional liability in a firm's debt-to-equity ratio (total liabilities/total shareholders' equity), this approach might be convenient for analysts to compare firms within and across sectors. At the same time, regulators can assess carbon cost implications for high-emitting companies.

Governments can contextualise corporate value implications against societal costs during policy design when considering responsibility (and cost) assignment to emitters, product users or national expenditures. Signalling policy likelihood also increases carbon premium, offering another means of hastening controlled decarbonisation, restricting fossil extraction investment and reducing disruptive transition likelihood. Insurers can consider ongoing and increasing EW damages' probabilities, geographically and when providing emitter cover. Our model, therefore, provides analysts with an additional tool to assess EW-related climate risks.

The practical implication of our model is that investors, policymakers, accountants, and analysts can explore company value sensitivities to EW based on their emissions. As damaging extreme weather events occur, the implied liability risks for high-emitting companies would be expected to reduce their market valuations. Thus, high-emitting companies' stock prices might be expected to reduce following highly damaging EW events (such as hurricanes, extratropical cyclones, heatwaves, precipitation, flooding and droughts). This would make climate emissions risks more transparent and introduce a valuation differential that would reward low-emissions companies while making it harder for high-emissions firms to raise capital in financial markets. By facilitating capital raising for lower emissions companies, this would be expected to promote the necessary economic stimuli for firms to move towards a low-carbon economy.

For academic research, literature suggests current company valuations are unlikely to fully reflect potential EW liabilities and that analyses may be incorrectly focusing on current emissions instead of cumulative emissions. As high-emitting companies' valuations would be expected to be impacted by damaging extreme weather events, we recommend studies around these events to elucidate market responses. However, as Bolton and Kacperczyk (2021, 2023) noted, carbon premiums materialised between 1990 and 2017. Further, attribution of EW to cumulative emissions is relatively recent; we might expect market responses to high-emitting company valuations to be muted for earlier periods (e.g. 1990–2017) and only to become apparent more recently and moving forward. We recommend that extreme weather climate analyses include FAR or R_0 uncertainties which would assist sensitivity studies assessing likely ranges of EW liability estimates. However, a broader implication, as raised by Stern *et al.* (2022), is the crucial need for closer interaction between the disciplines of economic and climate science research.

A further strand of research relates to climate litigation. Our model helps litigation parties link perpetual and growing GW-related extreme weather event damages to emissions. Litigation studies (Sato *et al.*, 2024) can analyse stock price responses to legal process stages, to identify whether $\psi_{i,s}$ increases, as anticipated, or responds to political developments. Due to the uncertainties, sensitivities and assumptions discussed, our modelled liabilities are estimates. We demonstrate feasibility, highlighting crucial insights, including inexorable EW event damages following emissions with perpetual reoccurrence and increasing frequency. However, increasing emissions-related damages' transparency, may reduce societal acquiescence to firms' externalising emissions, perhaps through litigation, regulation or cost-internalising measures. Consequently, following damaging extreme weather events, high-emitting firms' valuations would better adjust to reflect their operations' climate damages, incentivising transition to cleaner activities. Testing this approach with real-life data is left to future research.

Appendix 1
EW Event Probability

Consider changes in annual extreme event probability from earlier date (t_k with probability p_k) to p_0 (at t_0). Emissions, climate feedback and other factors drive GW intensification. We approximate using the historical trend, considering evidence supporting linear event probability evolution.

IPCC (2021, p. 1523) states "*. . . increases in the intensity of temperature extremes scale robustly, and in general linearly, with global warming across different geographical regions . . . up to 2100, with minimal dependence on emissions scenarios*." Some nonlinearity appears probable "*The frequency of hot temperature extreme events will very likely increase nonlinearly with increasing global warming, with larger percentage increases for rarer events*" (p.1518). The rarest, most damaging events have the greatest frequency change uncertainty. Figure A1 shows the ratio of event probabilities with increased temperature versus pre-industrial times, p_T/p_k. For precipitation, drought, and heat events, p_T/p_k estimates support linear probability increases with increasing temperature (T).

However, since around 1965, global warming has increased approximately linearly (Figure A2).

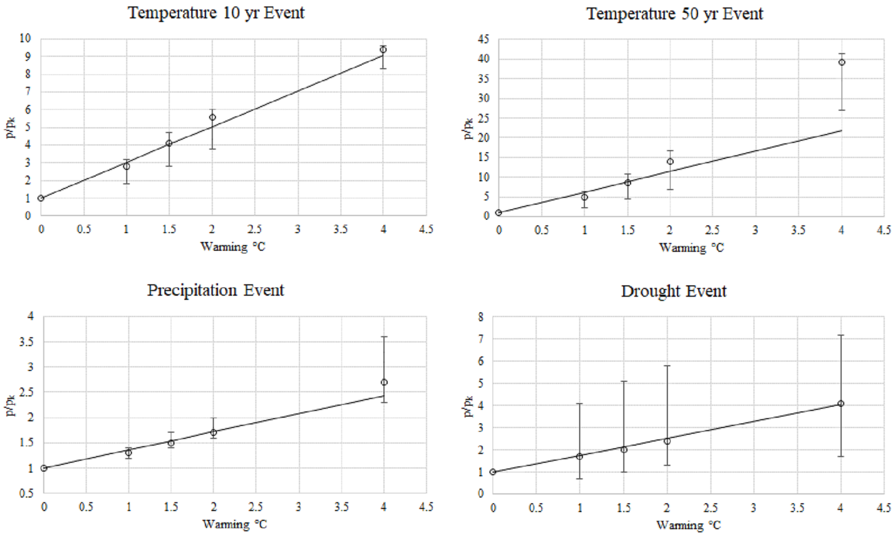

Figure A1. Extreme event probability increases with warming. Sources(s): Authors using data from Masson-Delmotte and Zhai (2022)

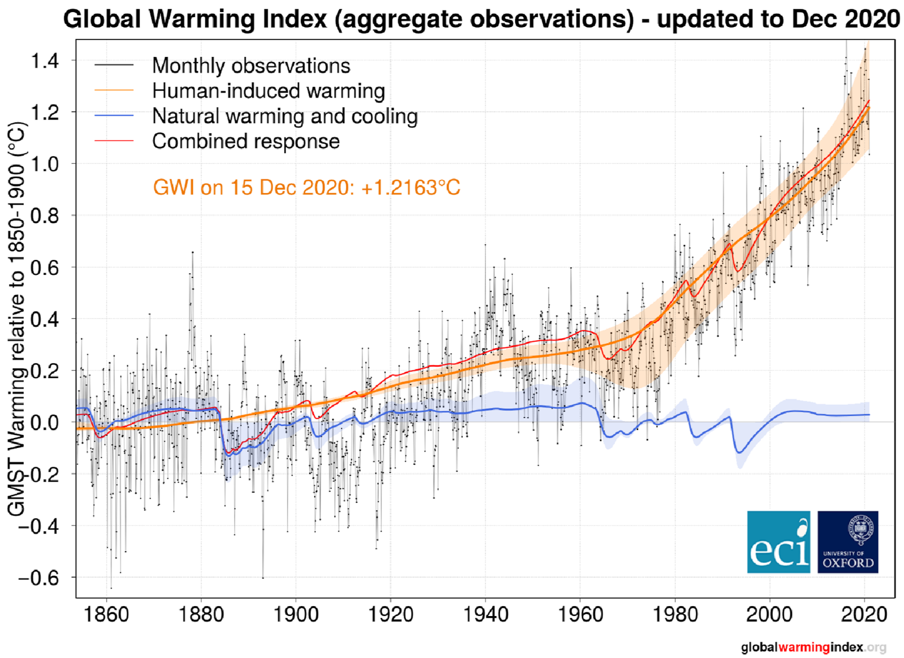

Figure A2. Global Warming Index showing warming against time. Source: Haustein *et al.* (2017, p. 3). The authors have made no changes

Hence, extreme event probabilities have evolved approximately linearly, since around 1965. As faster changes have occurred since 1965, taking $t_k \geq 1965$ counters underestimating GW intensification. Without better information, assuming linear annual event probability time-dependence appears reasonable (depending on future emissions), adjusted for $t_k < 1965$.

Appendix 2
Estimating EW liability growth rate

For GW intensification between t_k and t_0 with probabilities p_k and p_0 for similar events, $a_{i,0}$ increases with annual event probability (g differs from p_0 growth, as $p_k > 0$). Consider the 2017 North Atlantic hurricane season, annual probabilities increased from $p_k = 1/100$ in 1980 to $p_0 = 1/16$ in 2017 ($F_0 = 0.84$) over $\Delta t = t_0 - t_k = 37$ years. With two probability data points (1980 and 2017) we consider linear probability estimation defensible, which is also supported by the empirical climate data presented in Appendix 1. We therefore have:

$$p_t = \frac{dp}{dt} \cdot \Delta t + constant = \left(\frac{p_0 - p_k}{t_0 - t_k}\right)(t - t_k) + p_k \tag{B1}$$

where $\frac{dp}{dt} = \left(\frac{1}{16} - \frac{1}{100}\right)/37 = 0.0014\,yr^{-1}$.

Over one year, event probability increases from $p_0 = 1/16 = 0.0625$ to 0.0639, FAR increases to 0.8435, and return period decreases from $R_0 = 16$ to 15.65 years. Annual liability is $a_{i,0} = CL_{i,E}p_0 = D_E I \eta_i \Psi_i (p_0 - p_k)$. Assuming constant $D_E I \Psi_i$, we have the following algebraic formulation:

$$\frac{da_{i,0}}{dt} = D_E I\Psi_i\left[\eta_i\frac{dp_0}{dt} + (p_0 - p_k)\frac{d\eta_i}{dt}\right] \approx D_E I\Psi_i\left[\eta_i\frac{(p_0 - p_k)}{\Delta t} + (p_0 - p_k)\frac{\Delta\eta_i}{\Delta t}\right] \tag{B2}$$

Over a single year ($\delta t = 1$) we have $a_{i,0}(1+g)^1 \approx a_{i,0} + (da_{i,0}/dt)\times\delta t$ leading to:

$$g \approx \frac{1}{a_{i.0}}\frac{da_{i,0}}{dt} = \frac{D_E I\Psi_i}{D_E I\eta_i\Psi_i(p_0 - p_k)}\left[\eta_i\frac{(p_0 - p_k)}{\Delta t} + (p_0 - p_k)\frac{\Delta\eta_i}{\Delta t}\right] = \frac{1}{\Delta t}\left[1 + \frac{\Delta\eta_i}{\eta_i}\right] \tag{B3}$$

Estimating $\Delta\eta_i \approx \eta_i/\Delta t$ (constant annual increase), as cumulative emissions, temperature increases and event probabilities are linked, gives $g \approx \Delta t^{-1} + \Delta t^{-2}$. Typically, Δt exceeds decades, so $\Delta t^{-2} \ll \Delta t^{-1}$ and is negligible. Alternatively, assume $\Delta\eta_i \ll \eta_i$, that annual cumulative emissions proportion changes are negligible. Using $\Delta t = t_0 - \max(t_k, 1965)$, implying t_k no earlier than 1965 (see Appendix 1), we have:

$$g \approx \frac{1}{a_{i.0}}\frac{da_{i,0}}{dt} = \frac{1}{t_0 - \max(t_k, 1965)} \tag{B4}$$

As liabilities arise over Δt, by taking $t_k = 1980$ and $t_0 = 2017$, we have $g \approx 1/37 = 2.7\%$. Linearity implies a future date when annual event probability exceeds unity. For simplicity, we assume $a_{i,0}$ growth continues, perhaps via multiple annual events or increased intensity. Although linear extrapolation from the past is uncertain, this appears consistent with the empirical climate data presented in Appendix 1.

Notes

1. An accurate approach to evaluate climate risks is of significant interest for all agents within an economic/financial system. This includes central bankers (economic sustainability and stability), accountants (corporate valuations), financial analysts and investors (quantifying climate risks for portfolio diversification and asset allocation), bank lenders (lending decisions), insurers and actuaries (estimating relevant risk premiums).
2. Global warming is primarily caused by human activities to the extent that essentially all the current warming of 1.2 °C above pre-industrial levels is attributable to human activities (Haustein *et al.*, 2017) and hence referred to as “anthropogenic” (human-originating) global warming, or AGW. For accessibility, we use abbreviation GW (“global warming”) to refer to AGW unless otherwise stated. Readers familiar with climate literature may wish to mentally substitute “AGW” whenever we mention “GW”.
3. For more information, readers should refer to “Task Force on Climate-Related Financial Disclosures”/“International Financial Reporting Standards”, available at: https://www.fsb-tcfd.org/ and https://www.ifrs.org/sustainability/tcfd/.
4. Backward-looking principles for emissions responsibility are the “polluter pays principle” (PPP) and the “beneficiary pays principle” (BPP). Under the PPP, polluters should bear burdens from emission-causing activities (“you broke it, you fix it”), while the BPP states beneficiaries should bear the burdens (Garcia-Portela, 2023).
5. The need to produce new and diverse approaches in climate liability quantification for policy response purposes is also argued by Stern *et al.* (2022).
6. This is consistent with Laird’s (1919) theoretical principles. “[W]e should . . . select the simplest of any general propositions which may be true and ascertainable, since it is these truths only that are likely to aid . . . making further discoveries” (Laird, 1919, p. 343).
7. Hence, to potentially estimate individual stock price changes.
8. Legal or societal mechanisms transmitting these liabilities to emitting firms’ valuations are not considered here but left for future research.
9. Tol and Verheyen (2004) explicitly acknowledge the extreme difficulties of accurately estimating such damages.

10. For a more comprehensive coverage of the relevant literature, see Ackerman *et al.* (2009).
11. Such as embodied in the 2015 Paris Agreement.
12. Stern *et al.* (2022) believe special interests, including those from high-emission sectors, have used IAMs to promote muted climate responses, such as lowering the cost of carbon to $8 per ton.
13. Sato *et al.*'s (2024) study covers financial market response to 108 climate-related lawsuits against 98 major North American or European listed firms during 2005–2021. This includes cases based on corporate emissions exacerbating damages suffered from EW events.
14. For a comprehensive discussion of these challenges, readers should refer to Muniesa (2014). Muniesa argues that in economics, executed transactions and valuations are the reality "provoked" by theoretical models (for example, stock price discovery includes outcomes from pricing theories and exchange architectures).
15. For nine top high-emitting firms, Rayer *et al.* (2021) use $\eta = 0.145$.
16. These research questions will be addressed in future studies.
17. The resulting new policy environment might plausibly lead us to expect a reduction in $\psi_{i,s}$ during this period, in some cases.

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