Recalibrating Climate Risk

Aligning Damage Functions with Scientific Understanding

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Foreword

Mark Campanale, Founder and CEO, Carbon Tracker Initiative

To ensure the world accelerates investment for a new climate secure energy system, transitioning away from the old fossil fuel system, it's crucial pension schemes with long-term investment horizons send the market the right signal.

That investment signal has to be that a swift, orderly transition is in everyone's fiduciary best interests. Especially for younger scheme beneficiaries working today, who will experience extreme levels of economic disruption in their lifetimes, should emissions growth and climate change continue unchecked. Severe physical damage will be increasingly felt, even for diversified portfolios which offer limited defence against systemic climate risk.

As Professor Steve Keen and Carbon Tracker warned in Loading the Dice, this is not the message many pension scheme trustees receive. Investment consultants' climate scenario analysis and advice to clients follows the lead of the economists - who erroneously claim in published papers:

- Climate damages are best represented by a quadratic damage function, that cannot reflect non-linear acceleration in damages, such as those caused by climate tipping points - which can trigger irreversible shifts in earth system,
- The short-term negative impacts of climate policy (aka 'transition risk') are greater than the mid-long-term negative impacts of physical climate damages (physical risk) and,
- Strong GDP growth will continue undisrupted into the future, despite the growing impacts of climate change, increasingly felt via inflation and other poorly measured channels.

A common misconception of climate-related GDP damage figures is to assume that 20% GDP damage means taking a baseline of 100 and subtracting 20% = so an economy structurally smaller at 80% the size of what we have today.

However, economists (via the shared socio-economic pathways, SSPs) have created a magical economy whereby 3% annual GDP growth continues indefinitely into the future, irrespective of climate change damage severity. And only then, is 20% subtracted from that growth enlarged total pie, of a fictional future world without climate change. At no point do economists models factor in the possibility of the economy structurally declining in size.

Climate damages, when annualised are relatively trivial, at less than -0.5% GDP per annum. The net result of flawed economic advice is widespread complacency amongst investors and policymakers, with many investors viewing climate scenario analysis as a tick-box disclosure exercise. This manifests as failure to challenge and rapidly adapt investment strategies, with investors instead being advised to “transition at the speed of society.” Advice which openly invites the collective failure of international climate targets, gift wrapped in the language of caution and prudence.

In 2025, Norges Bank Investment Management (NBIM) rejected the advice of its consultant MSCI showing just 2% future damage from climate change. NBIM conducted its own top-down analysis arriving at a 19% damages figure. Yet rather than pivot its strategy, leaning into decarbonisation to encourage a faster transition, NBIM appears headed in the opposite direction, lobbying the Science Based Targets Initiative (SBTi) to weaken its climate target from 1.5°C to 2°C.

We recently witnessed a similar market impulse to weaken climate damage assessments when the NGFS v5 scenarios cited the Kotz et al Nature paper to justify a 300% increase in damage estimates from previous iterations. The paper was challenged via academic and finance industry pressure and ultimately withdrawn (the authors are currently correcting and will resubmit).

Where academic papers have consistently under-estimated climate damages, such as the work by William Nordhaus and Richard Tol, we note there has been no such coordinated attempt to correct the public record and withdraw erroneous or misleading papers that understate climate risks. As climate risk advice is an activity unregulated by the Financial Conduct Authority, no Government agency has taken responsibility for correcting the systemic under-pricing of climate-related financial risk.

Until the gap between scientists and economists’ expectations of future climate damages is closed, and Government bodies act to ensure the integrity of advice upon which investment decisions are made, financial institutions will continue to chronically under-price climate risks, and pension funds and taxpayers will remain dangerously exposed.

Executive Summary

Economic damages from climate change have long been underestimated and inconsistently represented in policy and financial decision-making. Recent academic developments - most visibly the withdrawal of 'the Economic Commitment of Climate Change' (2024) - have reignited debate in climate economics as to how damage modelling should be conducted, improved, and interpreted by policymakers.

At the same time, geopolitical consensus on climate action is weakening, even as physical climate risks intensify. This combination creates a growing gap between real-world climate risk and the economic analysis used to guide policy, supervision, and investment.

Recalibrating Climate Risk responds directly to this challenge. Drawing on expert judgment from more than 60 climate scientists, the report examines how risks evolve as warming increases and where conventional economic models begin to fail.

For treasuries, regulators, advisory agencies, and institutional investors, this report converges on a single conclusion: climate change introduces forms of risk that exceed the design assumptions of existing economic and financial frameworks. The appropriate response is not to wait for perfect models, but to recalibrate governance toward precaution, robustness, and transparency, recognising that avoiding irreversible outcomes is ultimately less costly than attempting to price them after the fact.

1. Climate damages are not marginal: they are structural

A central finding is that most existing economic frameworks implicitly treat climate change as a *marginal shock* to otherwise stable economic systems. This assumption no longer holds. At higher levels of warming, climate impacts increasingly disrupt multiple sectors at once; interact across regions through trade, finance, migration, and geopolitics; and trigger non-linear responses in environmental and human systems.

Rather than simply reducing output, climate change is likely to reshape economic structures themselves – altering where people live, what can be produced, how infrastructure functions, and which regions remain economically viable. This distinction is critical for policymakers and financial institutions: risks that alter system structure cannot be assessed using models designed for small, reversible shocks.

2. Extremes – not averages – define the future

Global mean temperature is an inadequate proxy for real-world risk. While economic modelling has traditionally linked damages to changes in global average temperature, societies and markets experience climate change through local and regional extremes, with heatwaves, floods and droughts bringing impacts that global averages overlook. The 2021 Texas winter storm illustrates this dynamic: temperatures barely registered in annual global statistics, yet the event caused over $195 billion in damages and grid failure affecting millions (Levin et al., 2022; Gruber et al., 2022; Castellanos et al., 2023; City of Austin and Travis County, 2021; Sugg et al., 2023). These extremes drive mortality, productivity loss, infrastructure failure, and political instability – effects that are poorly captured by mean temperature metrics.

As warming increases, the distribution of climate outcomes widens, with tail risks becoming increasingly important. From a financial stability perspective, it is these extremes – not median outcomes – that dominate systemic risk.

3. Rethinking economic metrics: beyond GDP

A major finding of our report is that GDP is too narrow to represent climate damages, with estimates significantly underrepresenting true economic, societal and environmental harm. GDP fails to capture human mortality, distributional impacts and inequality, cultural loss and displacement, ecosystem degradation, and disruption to social life. In some cases, GDP may even rise following disasters due to reconstruction spending, masking welfare losses entirely.

As a result, GDP-centred assessments can give policymakers and financial institutions a false sense of resilience, even as underlying vulnerability increases.

Among climate experts, there is a strong consensus on the need to complement GDP with metrics that better reflect lived economic reality and long-term societal stability. This is particularly relevant for ministries of finance and economic advisory agencies, whose responsibility for fiscal planning, debt sustainability assessment, and public investment will increasingly need to give a full reading of societal and economic health. Without broader metrics, climate risks will continue to be systematically discounted in macroeconomic planning.

4. Compounding risk and second-order effects

A central theme is the notion of compounding risks – instances where multiple climate impacts interact over time and across systems. When you speak to experts across the scientific community, it quickly becomes clear that climate risk is cumulative, interactive, and reinforcing.

We see examples of this when repeated extreme weather events can reduce a region’s recovery capacity, or when climate shocks in one area cause ripple effects across food systems, supply chains, and global markets. These second-order effects mean that climate damages cannot be understood as isolated events. Instead, risks accumulate, reinforce one another, and can push systems toward instability. Puerto Rico's sequential hurricanes exemplify this: Irma and Maria struck in 2017, then Fiona hit in

2022, with each storm striking before full recovery from the previous one, progressively degrading grid resilience and critical infrastructure (US Government Accountability Office, 2022; Hain et al., 2023; Kenner et al., 2023; Farnsworth et al., 2025; Anagnostakos et al., 2023).

For supervisors and financial institutions, this insight aligns closely with emerging work on systemic materiality of climate risk, particularly within European and international regulatory environments. These insights reinforce that climate risk assessment must move beyond asset-level exposure toward system-wide vulnerability.

5. Rising uncertainty at higher temperatures

An important finding challenges a foundational assumption in integrated assessment models (IAMs). Standard IAM practice typically assumes that uncertainty remains roughly constant across temperature ranges, often represented through symmetric error bars or stable probability distributions.

Expert judgment suggests the opposite. As the climate system moves further from historical conditions, physical responses become less predictable, social and economic reactions become harder to model, and the likelihood of unprecedented outcomes increases. In short, uncertainty widens with warming. This has profound implications for risk management. At higher temperatures – particularly beyond 2°C – confidence in precise damage estimates declines sharply, even as potential consequences grow. From a precautionary standpoint, rising uncertainty should increase, not decrease, the urgency of action.

6. Tipping points and the limits of economic modelling

Our report highlights the increasing probability of crossing critical tipping elements as global temperatures approach and exceed 2°C. Once triggered, Earth system tipping points may lead to irreversible environmental change, bringing long-lasting economic disruption and impacts that cascade across systems. These outcomes challenge the very foundations of conventional economic modelling, which assumes linearity, continuity, and stable preferences.

Further, scenarios that extend beyond median collapse thresholds should be treated with extreme caution. At sufficiently high levels of warming, economic models may no longer provide meaningful guidance, with outputs giving the illusion of numerical precise while resting on assumptions that no longer hold.

Conversely, experts stress that traditional economic models can also overlook more positive 'non-linear' effects in how societies adapt – such as positive tipping points in renewable energy and clean transport – meaning that their potential for delivering potentially *exponential* benefits on society, investment, and economic growth could appear more limited in traditional forecasting that fails to account for these compounding and cascading effects.

For policymakers, economic modelling should not be interpreted as forecasting under extreme warming and apparent precision should not be confused with reliability. Instead, scenario results must be contextualized within known limits of knowledge. We would urge institutions to explicitly acknowledge these limits – the tendency to overlook *both* systemic risks and the upside of clean energy investment - rather than allowing these flawed outputs to guide decision-making by default.

7. Implications for financial regulators and central banks

The findings of this report reinforce that climate change constitutes a core financial stability risk, which undermines the necessary conditions for economic growth. Climate impacts are likely to amplify traditional drivers of instability – including macroeconomic downturns, supply-chain disruption, geopolitical stress, and capital destruction – and can generate system-wide shocks even when global averages appear moderate. The 2022 Pakistan floods displaced 33 million people, caused $30 billion in damages, and triggered sovereign debt restructuring negotiations, yet contributed negligibly to global mean temperature statistics for that year (World Bank, 2022; Waseem & Rana, 2023; Iqbal, Nazir, & Khurshid, 2024; Manzoor et al., 2022). The 2021 Pacific Northwest heatwave shut down critical infrastructure across multiple countries simultaneously (White et al., 2023), while 2022 Rhine River low-water levels disrupted European industrial supply chains (Ademmer, Jannsen, & Meuchelböck, 2023; Gobert & Rudolf, 2023; Lentz, Graham, & van Vliet, M. T., 2024), demonstrating how localized climate extremes cascade through interconnected systems despite minimal changes in global average temperature.

For supervisors, this has direct implications for climate risk assessment and stress testing. Current approaches often rely heavily on mean temperature pathways, smooth damage functions, and point estimates that suppress tail risk and understate deep uncertainty. Yet expert judgment indicates that low-probability, high-impact outcomes dominate climate risk at higher levels of warming.

Our report supports supervisory practices that place greater emphasis on extremes, compounding effects, tail risks, and systemic vulnerability. Stress tests should explore ranges of plausible outcomes rather than single trajectories and explicitly acknowledge where modelling limits prevent reliable quantification. From a prudential perspective, the objective should not be to price climate risk with precision, but to ensure the resilience of the financial system against destabilising outcomes.

8. Implications for institutional investors and pension funds

For long-horizon investors, the report challenges the assumption that climate risk can be adequately captured through conventional financial metrics alone. Expert consensus emphasises that social and environmental disruption ultimately translate into economic and financial impacts, particularly over the timeframes relevant to pension liabilities and intergenerational investment.

Climate damages may also weaken the historical relationship between economic growth and asset returns, especially where GDP growth is driven by reconstruction rather than underlying wealth creation. This raises the risk that portfolios may appear resilient under standard macroeconomic indicators while experiencing rising exposure to physical disruption, regional concentration, and correlated shocks.

The report highlights the need for institutional investors to place greater weight on tail risks, systemic exposure, and the limits of diversification. Because climate change operates through shared physical systems, supply chains, and financial networks, it cannot be fully diversified away. Mitigation and transition pathways therefore function not only as ethical considerations, but as essential strategies for reducing long-term portfolio risk in a destabilising macroeconomic environment.

9. Implications for economic advisory agencies and scenario providers

The report identifies important limitations in the way climate damages are currently represented in economic analysis used to inform public policy. Expert elicitation shows strong consensus that prevailing damage functions rely excessively on extrapolation beyond observed climate conditions, suppress non-linear impacts, and convey false precision at policy-relevant warming levels.

At temperatures above 2°C, divergences in damage estimates are driven primarily by structural uncertainty (disagreement about how systems behave under unprecedented conditions) rather than by data gaps that can be resolved through further refinement. This challenges the practice of presenting single "best-estimate" projections as a basis for policy planning.

Adopting these recommendations would: improve alignment between economic modelling and scientific understanding, reduce underestimation of tail risks at higher warming levels, increase transparency of assumptions and limitations, and enhance the credibility of NGFS scenarios for financial supervision and macro-financial risk assessment. Most importantly, it would ensure that climate scenarios support risk management under deep uncertainty, rather than optimisation around a single 'best estimate' trajectory.

Section 1. Mind the Gap - the disconnect between climate science and economics

Throughout recent history, economic modelling has largely failed to capture the severity of climate damages and risks (Pretis & Allen, 2023). This is due to a legacy of traditional economic approaches which have significantly underestimated the impact of climate change on the global economy, by assuming the two as roughly linear – with some economists predicting damages as low as 2% GDP for a 3°C rise in warming (Tol, 2009).

Given the primacy of economic growth (as measured by GDP) as a decision-making metric among policymakers and financial institutions, there is a high possibility this 'lag' in forecasting has contributed – significantly – to a similar lag in effective climate policy, action, and adaptation. Today, the translation of climate damages into GDP losses is not a fringe issue: it is a central task of government treasuries, central banks and economic advisory agencies around the world. Consequently, the discrepancy between scientific predictions (of climate damages) and economic forecasts (of GDP losses) is a universal problem across financial markets and states which requires immediate intervention from financial policymakers, treasury officials, and central banks.

Recent progress

A central tool here is the **damage function** - a metric used in Integrated Assessment Models (IAMs) to assesses the economic impact of climate change, which has historically used mean annual temperature as the key climate variable (Howard & Sterner, 2017).

Recent research by Kotz et al. (2024) and Waidelich et al. (2024) has expanded the 'damage function' to include temperature variability, precipitation patterns, and other factors (Mankin et al., 2019; Damania et al., 2020), finding substantially higher economic impacts than previous estimates (Kalkuhl & Wenz, 2024). Earlier work establishing the empirical relationship between temperature and economic growth demonstrated that warming impacts warrant more stringent mitigation policy than previously recognized (Moore & Diaz, 2015).

Following this, the Network for Greening the Financial Sector (NGFS) – an influential group of central banks and supervisors who most governments and financial institutions base their analysis and, in turn, climate policy upon – adopted the updated 'damage function' from Kotz et al. (2024). As a result, the NGFS now estimate that climate change could damage 30% of global GDP growth by the end of the century (at 3°C under current policies), up from its previous estimate of 7-14% at the same temperature level (NGFS, 2023).

However, it is important to note that the Kotz et al. (2024) paper was retracted in December 2025 due to methodological and source data issues identified by the scientific community. The issues stem from the results being sensitive to removing one country, Uzbekistan, where the economic data for 1995–1999 had some errors and the impact of spatial autocorrelation on the uncertainty. The authors updated the analysis by correcting the underlying Uzbekistan data and accounting for spatial autocorrelation. After these corrections, the mid-century estimates of climate damages for the 1.5°C pathway changed: the uncertainty range widened (from 11–29% to 6–31%), and the chance that damages would differ across emission scenarios by 2050 decreased (from 99% to 90%). Despite this, the paper's median damage estimates are only slightly affected (17% instead of 19% by mid-century) and the corrected findings will be resubmitted to the journal *Nature* in due course.

How Damage Functions Are Constructed

Damage functions are created by analysing historical relationships between climate variables (primarily temperature) and economic impacts, then extrapolating these patterns to predict future damages under different warming scenarios. Economists typically fit mathematical functions - most commonly quadratic equations – to historical data showing the relationship between temperature changes and economic losses. However, this approach has significant limitations: the historical data may not contain a clear "footprint" of climate change impacts, and the choice of functional form critically determines the results. While quadratic, exponential, and logistic functions may fit current data equally well, they produce dramatically different predictions when extrapolated beyond existing temperature ranges (Dietz & Stern, 2015). Recent multi-model analyses comparing alternative damage specifications suggest that optimal warming targets may be lower than conventional quadratic functions imply (Van Der Wijst et al., 2023).

Quadratic functions, favoured by most economic models, cannot capture climate "tipping points" or other nonlinearities and predict relatively modest damages even at high warming levels (Lenton et al., 2019; Lontzek et al., 2015). In contrast, exponential and logistic functions – which can model accelerating damages as tipping points are crossed – suggest much more severe economic impacts could occur this century rather than in distant future periods. This mathematical choice essentially determines whether climate damages appear manageable or catastrophic (Weitzman, 2009, 2012 ; Pindyck, 2017).

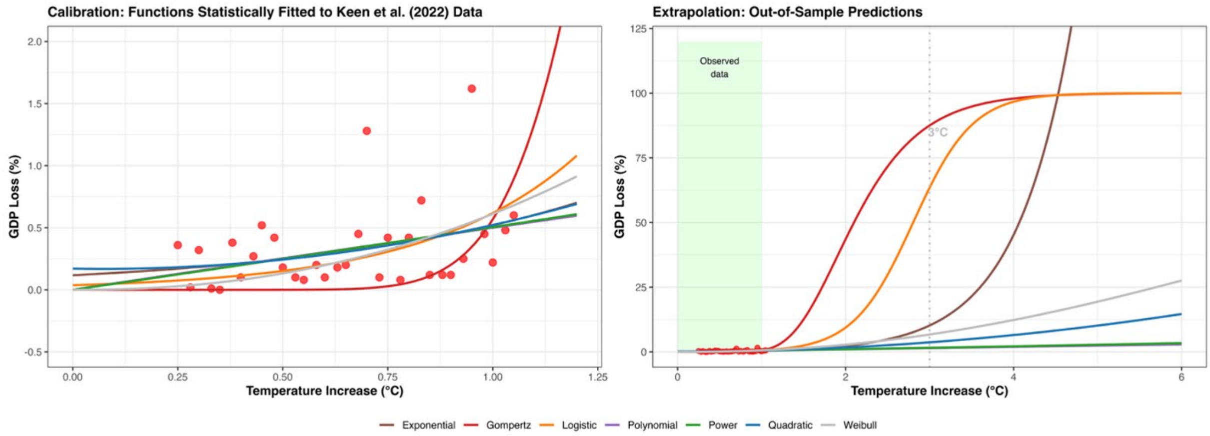

Figure 1. Various functional forms fitted to observed damages

What's missing?

However, as Kotz et al. (2024) and others acknowledge, while recent revisions do a much better job of capturing economic damages, they do not capture the full range of climate risks and impacts.

These estimates ignore several important factors, including direct effects of heatwaves, rising sea levels, damage from tropical cyclones, and potential climate tipping points. They also fail to account for non-economic impacts of climate change, particularly to ecosystems and biodiversity, as well as human health and wellbeing. One final point often missed is that GDP is only one metric of economic performance. In reality, climate shocks can trigger sharp declines in other areas – affecting physical capital, labour productivity and supply chain integrity, often far worse than headline GDP losses (Watkiss & Benzie, 2021), where destruction can be sudden and severe, even if growth merely slows. Such shocks can also have a profound socio-economic impact, with climate-related disasters, crop failures and droughts triggering mass migration and conflict over resources; in the decade up to 2025, climate disasters displaced 250 million people globally (UNHCR 2025). The narrow focus on GDP output, inherent in several prominent IAMs, also understates the negative impacts on capital investment, which have been shown to cause additional, long-run damages (Casey et al., 2024). Systematic analysis also confirms that conventional damage functions miss critical risk categories including tipping points, ecosystem collapse, and compound extreme events (Rising et al., 2022).

Recalibrating Climate Risk

The divide between scientists' and economists' estimations of climate damages is where this project begins. Through an expert elicitation with climate scientists, we aim to establish an emerging consensus on the scientific issues and inaccuracies with damage functions (and damage modelling more broadly), and the next steps for bringing them in line with the latest scientific knowledge on climate impacts and risks (Howard & Sterner, 2017).

Expert Elicitation Process

The project took the following approach, with the aim of creating an initial framework and set of results for improving climate damages that can be expanded in future:

1. **Survey Design**: careful survey design for the expert elicitation, informed by preliminary analysis, framework scoping, and review of issues within the damage function literature.
2. **Survey Dissemination**: the expert elicitation was issued to over 600 climate scientists, through a combination of direct outreach (to connections and identified targets), activation through networks (including the Global Tipping Points community and 2025 conference delegates) and ambassadors at leading climate institutions (including University of Exeter, UK Met Office, Potsdam Institute for Climate Impact Research, and University of Oslo).
3. **Virtual workshops** were conducted to complement the survey process, allowing for deeper discussion of the issues within damage functions, prioritisation of approaches to improve them, and informing the development of methodology for the larger project.
4. **Analysis:** Throughout the expert elicitation, we refined questions and aimed to establish consensus on the issues within damage functions. Survey questions and workshop responses were carefully recorded and analysed, informing the development of the initial methodology, developments, and recommendations in Sections 2, 3 and 4.

Stakeholder Engagement

Across the expert elicitation process, over 500 climate scientists were invited to take part. Of these, 335 were approached directly, after being identified through research and membership of prominent climate science networks. We anticipate a further 300 were reached via a combination of formal and personal network engagement – e.g. supportive academics and participating experts sharing the survey with colleagues and collaborators.

In total, 73 climate scientists engaged in the expert elicitation process. Of these, 68 completed the expert elicitation survey and a further 20 scientists took part in three virtual workshops that were held. An additional five left feedback but declined to complete the formal expert elicitation, for reasons outlined below.

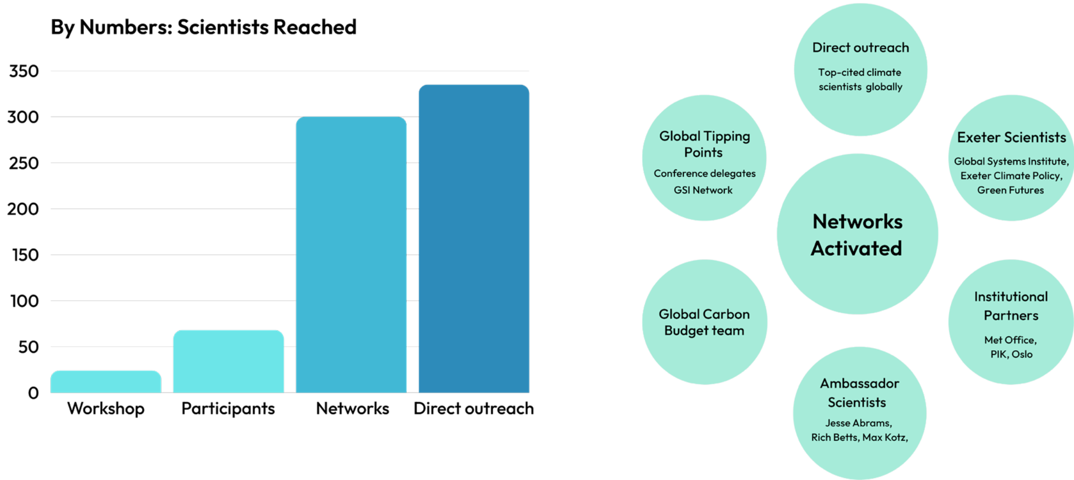

Figure 2. Scientists (left) and networks (right) engaged in expert elicitation process.

A cross-disciplinary reluctance?

Initially, some climate scientists were reluctant to complete the expert elicitation, due to hesitance about their authority to comment outside their direct area of expertise. In the initial outreach, around 20% of scientists engaged had written back to us with concerns about questions on economic impacts and damage functions being too technical or specialist, with some declining to complete the initial survey due to a perceived lack of qualification.

Consequently, we created a second survey, with a set of adapted questions focusing on climate impacts and their patterns, metrics, and associated weather variables – as relevant to economic damages. This second set removed a more technical question asking scientists to project the economic cost of climate damages, which had drawn hesitation. Following this, 20 scientists completed the second survey, eliciting responses from a total of 68 scientists across the two surveys. The following analysis is based on the merged results of both.

This reluctance to comment across disciplinary boundaries is an important finding itself, however, with comments from scientists evidencing a high degree of caution in giving estimates despite having opinions on the issues at stake: *"I agree that damage should look beyond global/regional GDP, but this is based on my uninformed opinion"*. Future research should seek to address this disciplinary discrepancy, by (for example) creating forums and working groups to increase dialogue as well as encouraging climate scientists to share informed views on damages. More focus is given to this issue in Section 4.

Despite the hesitance, overall representation was strong, with academics representing a wide range of countries in the Global North (USA, UK, Germany, Australia, France, China, Netherlands, Spain, Norway, Canada, Austria and Sweden) and research institutions, including universities (e.g. Columbia University, PIK, Nanjing University), research agencies (e.g. British Antarctic Survey, Lawrence Berkeley National Laboratory), and government agencies (e.g. UK Met Office, NASA Goddard Institute for Space Studies, European Commission). Next steps outlined in Section 4 include a plan to increase this participation further, especially in the Global South.

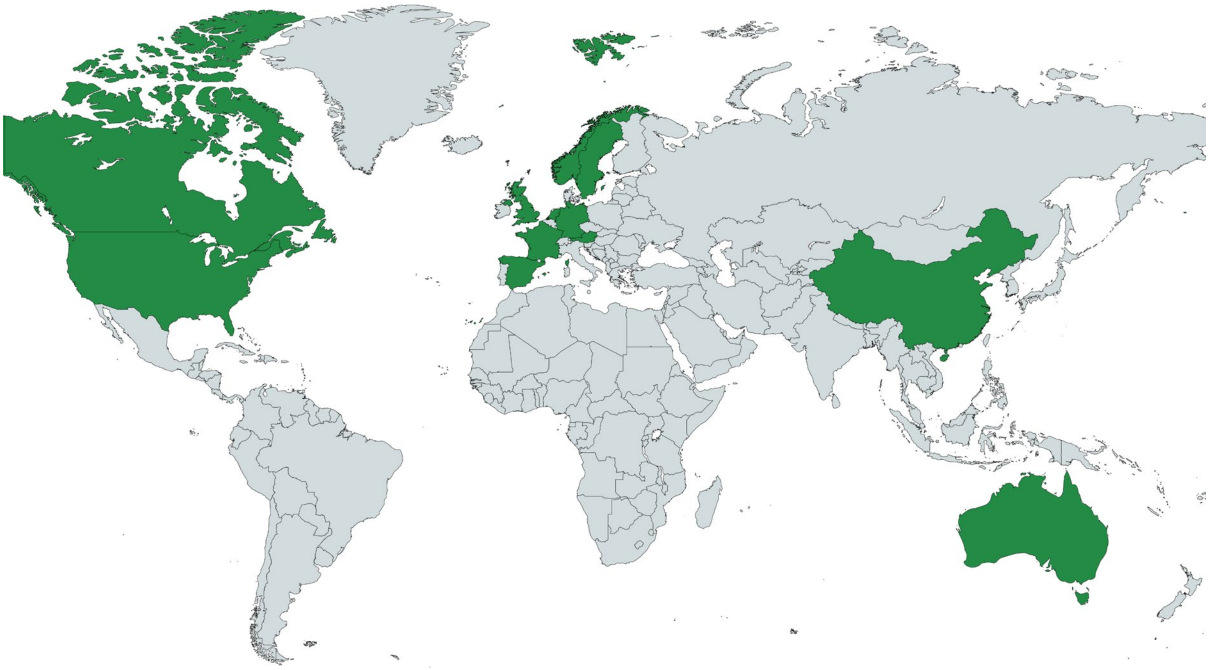

Figure 3. Expert representation by country.

Scope and intended audience of this report

This report addresses two distinct but interconnected dimensions of climate impacts, each relevant to different decision-makers: (1) economic impacts affecting financial asset values and portfolio performance over investment horizons, and (2) broader social and human welfare impacts, including mortality, health burdens, inequality, ecosystem degradation, and quality of life. The first is directly relevant to pension funds, institutional investors, financial regulators, and central banks using climate scenarios for stress testing. These include GDP losses, capital destruction, productivity declines, and disruptions to revenue streams that translate into asset price changes. Specifically, this report addresses several shortcomings in current approaches to forecasting said economic impacts, which analysts at government treasuries and economic advisory agencies may find particularly constructive. The second point is the primary concern of policymakers, governments, and civil society, particularly regarding vulnerable populations and distributional justice.

While these audiences have distinct mandates, we argue they cannot be cleanly separated in climate risk assessment for three reasons: (1) social impacts become economic impacts, (2) fiduciary duty extends beyond pure returns – and increasingly so -, and (3) current models systematically miss material risks by excluding social dimensions. Ultimately, climate change carries systemic risks that – when taken together – threaten the long-term financial stability that supervisors and regulators across the globe have a mandate to protect.

Section 2. Scientific Understanding – what's wrong with damage functions?

Summary findings:

- Overall, extremes – not averages – define the future. While mean annual temperature and GDP provide a proxy for specific climate and economic impacts, experts think they miss more than they capture.
- Most believe current damage estimates are far too low. Impacts will be non-linear, regionally uneven, and driven by extremes, not gradual averages.
- GDP losses alone underestimate real harm because they hide local destruction, social disruption, and human suffering behind small global numbers.
- Tail risks, thresholds and tipping points dominate their thinking: once critical limits are passed (e.g. mean annual temperatures beyond 25°C), impacts escalate sharply.
- Adaptation is unpredictable and limited. Societies don't adjust smoothly or indefinitely; some systems simply reach points where adaptation fails. If our agriculture system fails, for example, the knock-on impact of widespread hunger – through labour shortages and social unrest – would be far greater and disproportionate to the 4% of global GDP the sector currently makes up.
- Cascading risks are largely absent from current modelling. For example, climate shocks leading to crop failures, food-price spikes, migration, and conflict.

Throughout the expert elicitation, there was strong agreement that standard economic models seriously underestimate the real risks from climate change, with many climate scientists finding that linear damage curves do not match what they observe in science.

2.1. Extremes, not averages, define the future

Many stressed that it is extremes, not averages, that define the future (Kotz et al., 2024). Broadly, participants viewed mean annual temperature as a somewhat useful proxy for other weather and climate effects that, if incorporated, could give a clearer link between cause and likelihood of climate damages. One participant noted that heat waves and floods already kill hundreds of thousands each year, and that these kinds of events will impact lives and livelihoods far more than slow temperature changes. Yet most damage functions still rely on global mean temperature as the main driver.

This focus on extremes rather than averages has profound implications for how we assess climate risk. The relevant question for investors and policymakers is not "what is the most likely outcome?" but rather "is the probability of catastrophic outcomes acceptably small?" The Institute and Faculty of Actuaries' framework illustrates this principle: climate risk has a long, dangerous tail where low-probability, high-impact events dominate the risk calculus (Trust et al, 2024, 2025). While traditional risk assessment focuses on median temperature projections (e.g., 2.7°C under current policies), tail risk management asks whether we can tolerate even a 1% or 0.1% chance of reaching temperatures associated with societal collapse. This reframing shifts attention from managing the most likely outcome to eliminating the possibility of civilizational-scale disasters.

Mean Annual Temperature

Relying on global mean temperature also oversimplifies a world full of local extremes. One participant noted that the northern hemisphere warms roughly twice as fast as the global average, so any “global” temperature hides huge regional differences (Bilal & Känzig, 2024). The global average remains popular as a simple and overarching narrative, but that simplicity comes at a cost. Economically, this matters: assumptions that the Global North will be largely immune to climate impacts are misleading, as faster regional warming can still drive shocks to infrastructure, supply chains, and financial systems.

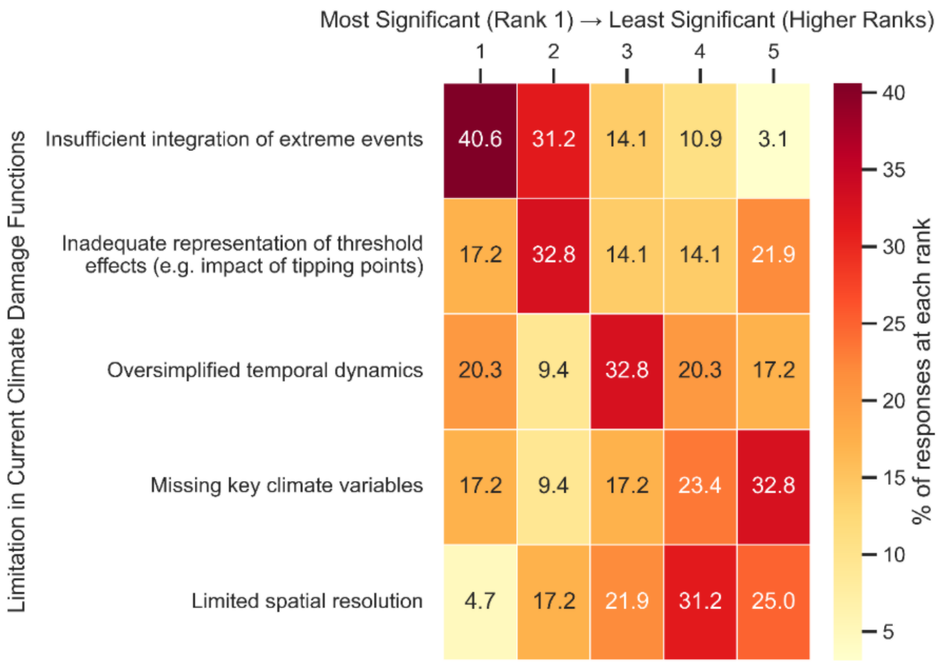

Figure 4. Expert-assessed limitations of current climate damage functions.

Respondents identify the most serious deficiencies (Figure 4) as the failure to integrate extreme events, the weak representation of threshold/tipping-point effects, and the use of oversimplified temporal dynamics. Missing climate variables and limited spatial resolution are also widely highlighted.

While there is acknowledgement that temperature can be a useful proxy for some climate impacts and weather patterns, it does not give a sound picture of the extremes and realities lurking beneath this average.

This emphasis on extremes and threshold effects connects directly to the challenge of tail risk assessment. When experts identify extreme events, tipping points, and nonlinear dynamics as the most serious deficiencies in current models, they are pointing to the mechanisms that generate the distribution's dangerous tail. A damage function based on mean temperature and smooth curves systematically underestimates tail risk because it cannot capture the cascading failures, threshold crossings, and compound extremes that drive catastrophic outcomes. For financial institutions and pension funds with fiduciary duties, this means current risk assessments may be dramatically underestimating the probability of portfolio-destroying outcomes.

Gross Domestic Product (GDP)

Another major issue raised – and a point of particular relevance to pension funds, given their fiduciary duty to consider the social context into which members will retire - is the over-fixation on Gross Domestic Product (GDP). As with mean annual temperature, GDP is a 'broad brush' aggregation that – while a useful proxy for impacts in certain cases – often lacks the specificity to be fully informative. Participants emphasised that GDP is too narrow to represent real human welfare - and ignores mortality, inequality, cultural loss, and the sheer disruption to people's lives caused by climate change (Costanza et al., 2014). Critically, GDP measures flows of economic activity rather than stocks of wealth: destructive events can increase measured GDP through reconstruction spending even as underlying assets, livelihoods, and resilience are permanently eroded. In this sense, standard damage functions systematically underestimate true losses by recording spending flows rather than the destruction of capital and wellbeing. As such, it doesn't capture structural change - climate shocks will likely reshape economies, not just shrink them, by altering sectoral composition, labour productivity, and capital allocation, rather than simply reducing output proportionally (Carleton & Hsiang, 2016; Diffenbaugh & Burke, 2019; Taconet et al., 2020; Calleja-Agius et al., 2021). This distinction matters for investors: the historical correlation between GDP growth and asset values can break down under climate stress, particularly when reconstruction activity masks declining wealth stocks.

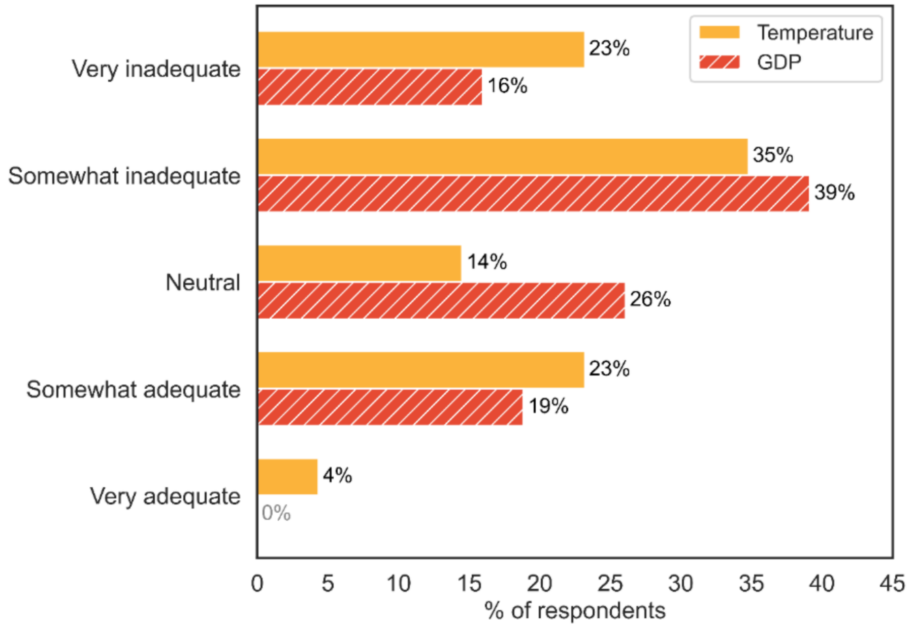

Figure 5. Adequacy ratings for mean temperature and GDP as standalone variables in damage functions.

Figure 5 shows how respondents rated the adequacy of global mean annual temperature and GDP as standalone variables in damage functions. Across all five categories, perceptions toward the two metrics follow a similar pattern: a clear majority regard both variables as insufficient, with the highest shares falling in the somewhat inadequate or very inadequate categories. Far fewer respondents consider either metric to be adequate, and almost none view them as very adequate. Notably, GDP presents a slightly more polarised assessment, with a larger fraction of respondents classifying it as somewhat inadequate or neutral compared to temperature. Overall, the distributions indicate strong scepticism toward relying on single-variable proxies for climate damages.

Several participants also criticised the focus on GDP within economic modelling, noting how national figures often hide the damage felt locally. One participant gave the example of a recent U.S. hurricane that had little effect on national GDP but wiped out roughly half of the affected state's economy. Another pointed out that Kiribati's GDP is negligible in global terms, so its complete disappearance would barely register in global statistics. Yet for its people, such an outcome would represent an absolute catastrophe- the loss of homeland, culture, identity, and sovereignty - highlighting how GDP weighting systematically downplays existential risks to smaller and poorer regions.

Respondents overwhelmingly view both global mean annual temperature and GDP as insufficient standalone indicators for modelling climate damages (Figure 6). A large share rated both variables as somewhat or very inadequate, consistent with workshop concerns that (i) averages obscure extremes, and (ii) GDP masks inequality, social disruption, and non-market losses. These results reinforce expert calls for expanding beyond single climate or economic proxies and incorporating extreme events, regional differences, and non-GDP welfare metrics into damage modelling (Diffenbaugh & Burke, 2019; Taconet et al., 2020).

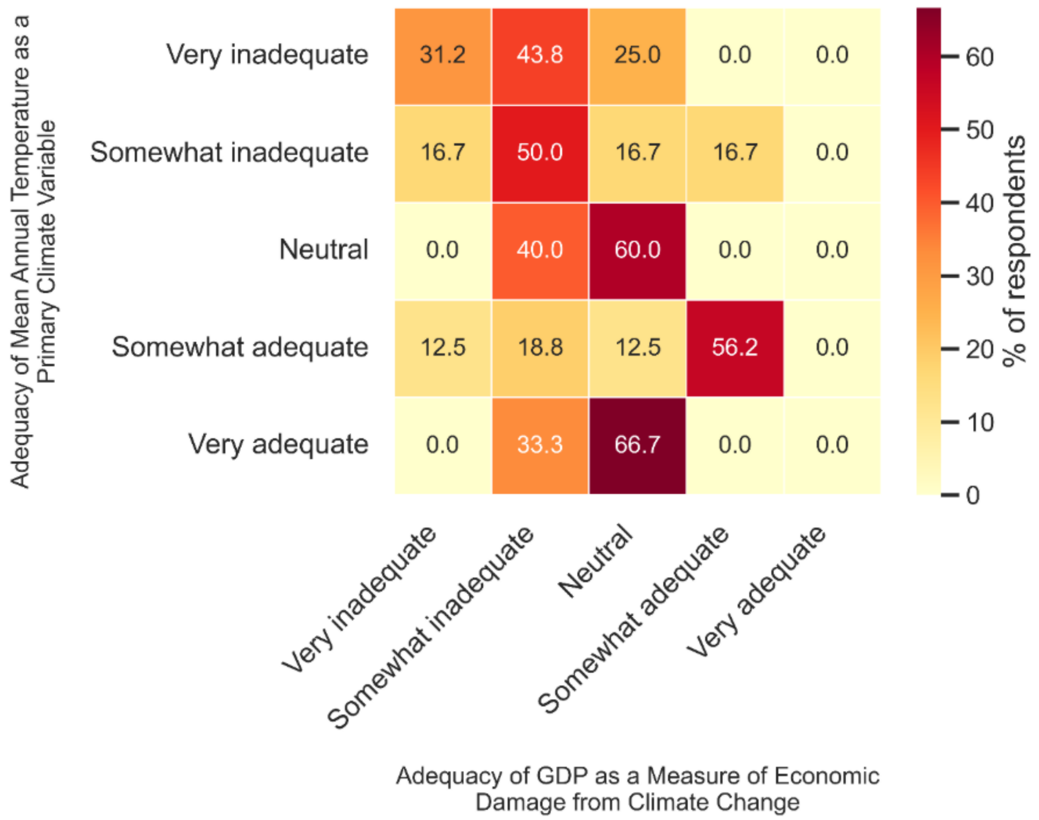

Figure 6. Perceived adequacy of mean temperature and GDP as key variables in damage functions.

However, participants acknowledged that GDP remains a practical and widely used benchmark in financial analysis. For investors and analysts, GDP is often a key driver of expected revenues, particularly in cyclical sectors such as construction, heavy industry, chemicals, and transport. As such, wholesale replacement of GDP with alternative welfare metrics - such as HDI, GPI, or inequality measures - may not be feasible in applied financial modelling, even if these metrics better capture social and environmental harm.

2.2. Damage, like progress, is not linear

Regarding the mathematical form of most damage functions, several participants said that this is fundamentally wrong. Real world (complex dynamic) systems, both physical and social, can change abruptly and nonlinearly once critical limits are crossed. This nonlinearity has critical implications for probability distributions of climate damages. When systems change abruptly at thresholds rather than gradually across all temperature ranges, the damage distribution develops what actuaries call a "fat tail" scenario with disproportionately severe impacts. A recent MSCI survey revealed a striking disconnect: 15% of investors expect temperature outcomes of 4°C or higher (MSCI, 2024), yet approximately 50% of climate scientists identify 4°C as approaching or exceeding the threshold for economic collapse. This disconnect illustrates why investor risk assessment must shift from asking "what's the most likely damage at 3°C?" to "what's the probability we cross catastrophic thresholds?"

A lot of the discussion focused on these nonlinear and threshold effects: the idea that things look fine until we cross certain limits, and then impacts shoot up fast. One participant mentioned work productivity limitation due to heat stress, noting that wet bulb temperatures of 35°C represent a human physiological limit (Vanos et al., 2023).

When it came to adaptation, participants agreed that the models are overly optimistic. Real-world adaptation doesn’t follow smooth, linear paths, it happens suddenly (as with the explosion of renewable energy and EV adoption) or not at all, depending on politics, technology, and social tipping points.

2.3. Damages are cascading and long-lasting

When it comes to cascading and systemic risks, almost all participants agreed that impacts don’t stay within one sector (Reith et al., 2024; Ortiz-Bobea et al., 2021; Moore et al., 2017). A heatwave can hit crop yields, raise food prices, cause unrest, and fuel migration, all linked together. Participants warned that our current models cannot capture these chains of events, even though they may cause the biggest damages overall. This has critical implications for how investors interpret climate scenarios.

The inability to model cascading risks creates a dangerous misinterpretation of climate damages. For investors, cascading risks transform diversifiable regional shocks into correlated systemic risks: a crisis in one region propagates through global supply chains and financial systems. For example, extreme floods and droughts can trigger severe food shortages and displacement, which in turn can trigger migration, conflict, even institutional breakdown. The ripple effects of such crises extend through the global financial system, where supply chains and commodity markets suffer. As global multi-hazard assessments show, compound climate events create damages exceeding the sum of individual hazards when extremes occur simultaneously or in rapid succession. Standard portfolio diversification - designed to manage uncorrelated regional risks - fails when cascading risks take hold.

Furthermore, global multi-hazard risk assessments reveal that compound climate events create damages exceeding the sum of individual hazards, particularly when multiple extremes occur simultaneously or in rapid succession (Stalhandske et al., 2024). Critically, these cascading impacts extend into capital and financial systems: investment portfolios, bank balance sheets, and corporate valuations are exposed to risks that standard climate scenarios often underestimate (Casey et al., 2022; Finance Watch, 2025. While it seems intuitive that climate shocks would propagate into the financial system, Nordhaus - and much of the mainstream literature - did not recognize this, noting that "for the bulk of the economy - manufacturing, mining, utilities, finance, trade, and most service industries - it is difficult to find major direct impacts of the projected climate changes over the next 50 to 75 years" (Nordhaus, 1991, p. 932).

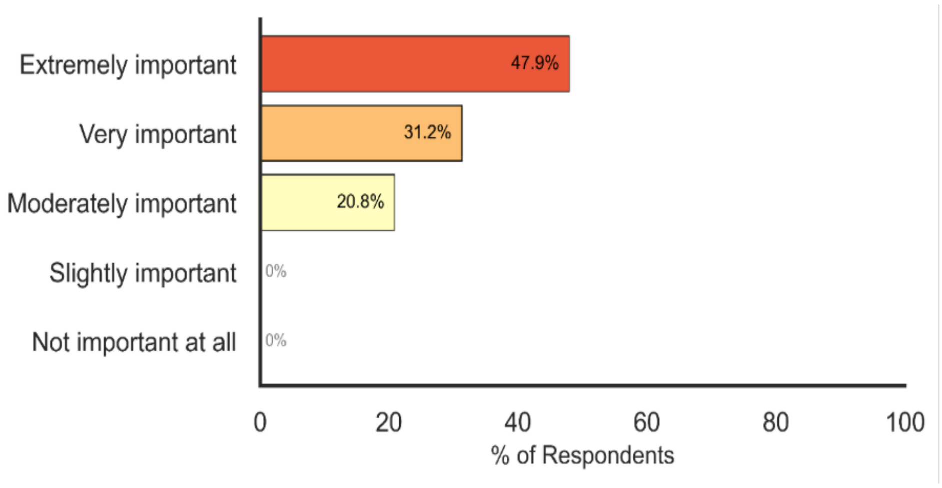

Figure 7. Perceived importance of representing interactions between climate impacts.

Nearly 80% of respondents consider climate-impact interactions "very" or "extremely" important (Figure 7). Experts stressed that heat, floods, droughts, and ecological shocks rarely occur in isolation; instead, they trigger compound and cascading effects that existing damage functions are not designed to capture. This reinforces the need for multi-hazard and systems-based approaches.

-

Overwhelmingly, participants also called out the unrealistic assumption of easy recovery – rejecting the assumption, common in many IAMs, that climate damages are short-lived and front-loaded.

-

Many integrated assessment models implicitly assume near-complete capital reformation within a year, an assumption that participants viewed as patently implausible considering well-documented physical, economic, and mental health impacts of disasters such as Hurricane Katrina. Most participants instead believed that economic impacts peak years after the initial shock, with 40% indicating that impacts stretch over multiple time periods and nearly a quarter reporting that more than 50% of total damages occur after the first year. This aligns with workshop insights emphasising slow recovery, cumulative losses, and non-linear economic scarring - especially in lower-resilience regions - where repeated shocks erode adaptive capacity rather than allowing full rebound (Scheffer et al., 2015; Burke et al., 2015; Diffenbaugh & Burke, 2019; Bastien-Olvera et al., 2024). In certain regions, like Vanuatu, local economies never entirely recover from multiple cyclones, as damages accumulate over time. Recent evidence from the San Francisco Fed reinforces this dynamic, showing that when investment is more vulnerable to climate shocks, short-run consumption losses may appear smaller, but long-run consumption losses are substantially larger - precisely the pattern that IAMs with rapid recovery assumptions fail to capture (Casey et al., 2024). Climate variability itself can therefore generate persistent and accumulating economic effects rather than temporary deviations from trend (Callahan & Mankin, 2023).

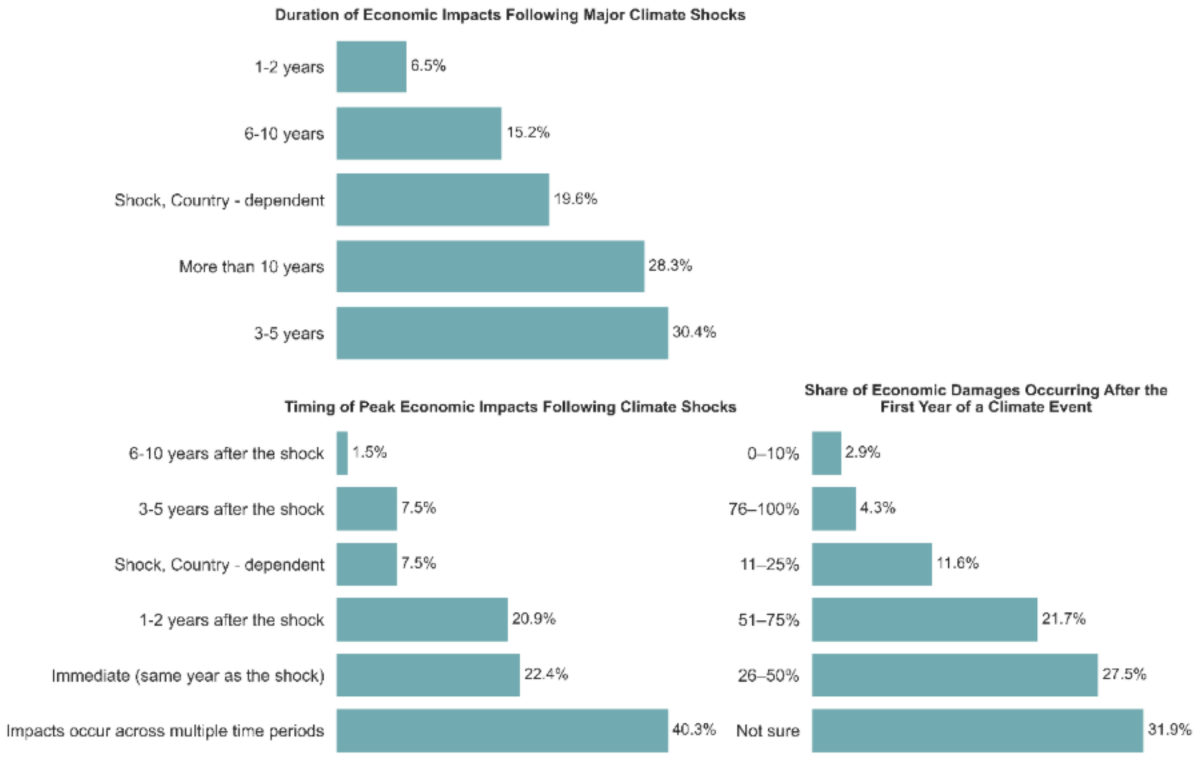

Figure 8. Estimated duration and temporal profile of economic damages following major climate shocks.

2.4. The limits to growth

A fundamental assumption pervades economic modelling: GDP always grows. Even projections showing severe climate damages - 19%, 30%, or 50% GDP losses - typically assume continued positive growth, just at reduced rates. This creates a systematic communication problem. When economists project 19% GDP reduction by 2050, policymakers often interpret this as the economy shrinking by one-fifth. In reality, it means the economy grows from 100 to 220 instead of to 270, both substantially larger than today. The "damage" is the gap between two hypothetical futures, not absolute decline. Reporting damages as percentage differences between hypothetical GDP levels obscures severity. A more transparent approach would be to report the decline in growth rates.

This framing implicitly assumes growth continues through catastrophic conditions. At 3-4°C, climate scientists expect food system failures, mass displacement, and institutional breakdown. The assumption that such disruptions merely slow growth rather than reverse it is questionable. Some economists continue to defend projecting positive growth under severe warming as reasonable extrapolation from historical patterns. However, this overlooks a critical distinction: unmitigated climate damage removes the necessary conditions for economic growth itself – food security, reliable water supplies, energy infrastructure integrity, and population health. When these foundational prerequisites collapse simultaneously, the empirical relationships between capital, labour, and output that underpin growth models cease to hold. The question is not whether growth slows from 2% to 1.2%, but whether growth remains structurally possible when the biophysical systems that sustain economic activity break down. Second, it obscures lived experience. Countries experiencing repeated crop failures and infrastructure destruction aren't "growing at 1.2% instead of 2.0%" - they may face absolute declines in productive capacity, even if reconstruction spending temporarily boosts measured GDP. Third, cascading risks erode baseline growth itself. Current models assume 3% baseline growth, then apply climate damages - producing "2% growth instead of 3%." But cascading mechanisms don't merely reduce growth rates. They erode the underlying capacity for economic functioning. The question becomes: can we maintain positive growth at all when food systems fail and governance breaks down? Cascading risks can drive growth from 3% to 0% or negative - actual capital destruction, not slower accumulation. For investors, this is the difference between lower returns and loss of capital.

The collapse threshold framework in Development 2 explicitly challenges this growth assumption by asking: at what temperature does continued growth become physically impossible?

2.5. Damage compounds across time, space, and sectors

Beyond the three specific priorities, survey responses revealed a fundamental cross-cutting concern: oversimplified temporal dynamics and limited spatial resolution are critical limitations of current approaches (Ricke et al., 2018; Cruz & Rossi-Hansberg, 2024), obscuring the reality that climate impacts vary dramatically by location, sector, and context.

While a global average temperature increase of 3°C might sound manageable, the regional realities can be catastrophic. Tropical regions already near physiological limits face devastation while some temperate regions see modest impacts. Low-income countries lacking protective infrastructure experience far greater damages than wealthy nations. Agriculture faces existential threats at warming levels where digital services remain largely unaffected - creating sectoral differences spanning orders of magnitude. Yet global aggregate functions average across these vastly different experiences.

Critically for financial regulators and policymakers, these regional extremes show how climate change compounds the traditional drivers of systemic financial risk – including macroeconomic downturns, geopolitical tensions, credit tightening, and liquidity stress. A climate event occurring during an economic recession would likely inflict far greater economic damage than during robust economic growth: corporate balance sheets are weaker, fiscal buffers are depleted, insurance capacity is constrained, and financial markets are less able to absorb correlated shocks. For example, flooding that destroys productive capacity during an expansion may slow growth temporarily, while the same event during a downturn could trigger cascading business failures, banking stress, and sovereign debt crises. From a financial stability perspective, stress testing and scenario analysis should explicitly model climate impacts under varying macroeconomic conditions, recognizing that the interaction between climate shocks and economic fragility creates nonlinear amplification of systemic risk.

Temporal aggregation creates similar distortions (Ortiz-Bobea et al., 2021; Moore et al., 2017). Current damage functions operate at annual resolution using mean temperature, obscuring seasonal variation critical to agriculture, the distinction between gradual changes allowing adaptation versus sudden shocks overwhelming capacity, and extreme events that drive much of actual damage. A 1% annual loss distributed steadily over a year differs fundamentally from 12% loss in one month - the latter destroys capital irreversibly and triggers cascading failures through supply chains. This distinction has important implications for adaptation: while gradual changes may be amenable to anticipatory investment, abrupt shocks can render adaptation ineffective or economically wasteful. Given this complexity and heterogeneity, damage functions should be viewed as a necessary but limited tool - useful where possible, yet constrained by temporal, spatial, and structural simplifications - underscoring the importance of complementary approaches such as risk registers and scenario analysis to identify where adaptation is viable and where resources may be better directed toward risk avoidance or mitigation.

These distinctions raise a critical but largely unexamined question for adaptation finance. Global estimates of adaptation needs – estimated to be US$310-365 billion per year for developing countries (UNEP, 2025) - typically do not distinguish between investments that reduce exposure to gradual, foreseeable change and those aimed at protecting systems vulnerable to abrupt shocks that may overwhelm adaptive capacity altogether. Where damages arise from sudden extremes that irreversibly destroy capital and propagate through interconnected supply chains, adaptation spending risks becoming reactive repair rather than resilience, or in some cases a misallocation of scarce capital. This has important implications given that adaptation and mitigation draw from the same limited pools of public and private finance (Elgersma, 2025). Without clearer guidance on where adaptation is likely to succeed, there is a real risk that scarce resources are diverted away from transition investments that could reduce systemic risk altogether. Improving climate models and risk frameworks to distinguish between adaptable and non-adaptable risks - and to identify where adaptation is likely to be effective versus where it is unlikely to prevent large losses (Wei, 2025) - would help ensure that adaptation finance is deployed efficiently, avoiding wasted capital or reinforced vulnerability, while prioritizing transition investments where they can most reliably reduce systemic risk.

Respondents emphasized that systemic and compounding social risks - including the breakdown of networks, migration cascades, and political fragility - often drive the most severe damages, yet spatial and temporal aggregation renders these invisible. Even if global GDP losses appear "moderate," catastrophic damages concentrated on vulnerable populations can create humanitarian crises that aggregate functions entirely miss. This highlights a form of survivorship bias in GDP data: by focusing on averages or regions that persist economically, models obscure populations and sectors that are most at risk. Addressing this requires more regular, granular, and mechanistically informed data, yet much remains missing because historical records are incomplete, local-level reporting is uneven, and conventional economic metrics were never designed to capture cascading social vulnerabilities.

2.6. Data and modelling issues

Participants also highlighted a broader data and modelling problem: most current damage functions are extrapolating far beyond the evidence available. Because empirical data only covers about 1.3 °C of historical warming, the models rely heavily on assumptions rather than observation. In some cases, the errors are even more basic. One participant mentioned a study claiming that collapse of the Atlantic Meridional Overturning Circulation (AMOC) would *benefit* the world by cooling the rich northern economies, specifically they state that it would reduce the social cost of carbon by 1.4% (Anthoff et al., 2016) - an outcome so illogical that the group agreed it exposed serious flaws in how GDP-weighted models represent climate risk and reliance on temperature-output relationships (Newell et al., 2021; Keen, 2022). Recent work has shown how specific climate-driven hazards, such as glacier retreat leading to increased outburst flood risks (Stuart-Smith et al., 2024), demonstrate the concrete physical mechanisms that aggregated models often miss.

Section 3. Bridging the Gap – improving damage functions

Summary:

- Improved damage modelling should focus on better understanding the drivers, localities and extremes that underpin changing temperatures and damages.
- Prioritise improvements *within* damage functions, but where this is not possible, alternative approaches should be considered for their accuracy, pragmatism, and decision usefulness.
- Prioritise the consideration and integration of other progress metrics alongside GDP, such as human wellbeing, health, mortality, and inequality.
- Prioritise process-based impact channels – e.g. modelling for specific climate impacts – to account for extreme events, cascading effects, local accuracies and cross-sector dynamics.
- Adaptation and tipping dynamics must be modelled explicitly, capturing timing, costs, and limits rather than assuming perfect adjustment.

3.1. Implications: how scientists would improve damage functions

Participants agreed that the goal isn't to throw out damage functions entirely, but to make them more reflective of real-world processes. A good first step is to **expand the climate inputs beyond global temperature**. Precipitation, humidity, sea-level rise, and the frequency of extreme events all need to be part of the picture. As one participant said, what people actually experience are local extremes, not global averages.

Models also need to handle **nonlinearity** and randomness. Climate and social systems don't behave smoothly; they shift suddenly once thresholds are crossed. New functional forms should be able to capture these jumps, not just draw smooth curves. Scale is another big issue. One participant suggested starting from the bottom up, using data at regional levels to build up to global results. That way, the diversity of local impacts is not lost in national averages.

Several participants called for a **process-based** or system-dynamics approach, where GDP is an outcome that emerges from all the interacting systems, including climate, energy, agriculture, labour, health, and so on (Coronese et al., 2024). Adaptation should also be modelled explicitly: when it happens, what it costs, and where it hits limits (Auffhammer, 2022; Andrijevic et al., 2024).

Figure 9. Perceived adequacy of GDP and expert-identified additional metrics.

On this point, Figure 9 shows how most respondents who consider GDP inadequate highlight the need for metrics that capture inequality, distributional losses, non-market damages, and physical destruction, dimensions routinely missed in GDP-centred approaches. This complements the workshop view that economic damages should reflect human wellbeing, structural change, and system-wide fragility rather than changes in aggregate output alone.

Following on from this, several participants suggested **broadening what we measure**. Participants recommended adding metrics like mortality, health outcomes, inequality, and displacement. Alternative metrics such as the Genuine Progress Indicator provide more comprehensive assessments (Kubiszewski et al., 2013; Fox & Erickson, 2020). One mentioned the Germanwatch Climate Risk Index as a good example of mixing economic and human indicators, while the other argued that showing the human lives lost or disrupted would make a bigger impact on public understanding than quoting percentage losses (Carleton et al., 2022; Bressler, 2021).

Participants also put forward the need for greater transparency in modelling, a suggestion which could help implement the broadening of GDP. Participants recommend that IAMs models be made open-source wherever possible (Moore et al., 2018), with clear documentation. This would avoid assumptions or coding errors can completely distort the message, and could also enable collaboration between disciplines – for example, researchers working on human health impacts aligning projections with current estimations of GDP impact.

Within the current approach, there is a clear need for more qualitative and local data, especially where statistics are poor. As participants remarked, historical emissions databases (Gütschow et al., 2019) and regional climate reconstructions (Guo et al., 2024) can help validate damage functions against observed impacts, while case studies from vulnerable regions (Castellanos et al., 2022) provide crucial context that global models miss.

The groups also discussed audience-specific communication, and the need to make strategic decisions about improvements and methods based on the audiences they serve. Where financial regulators may need numerical ranges, uncertainty intervals and scenario mapping, policymakers and the public need clear stories about human consequences (Barnett et al., 2020). Visual tools and risk registers can help impress these pragmatic messaging aims (Lenton et al. 2025; Lenton et al., 2019; Steffen et al., 2018). For example, a "tipping-point risk register" (Lenton et al. 2025) that compiles risks across sectors and temperature ranges, similar to the "burning-ember" graphics used in IPCC report, can make complex information far more digestible and decision-useful for policymakers.

Everyone agreed that fixes will only work if they are accompanied by stronger **collaboration** across disciplines. At present, economists, climate modellers, social scientists, and financial practitioners tend to work in silos. Yet finance plays a critical role in translating climate damages into asset valuations, capital allocation, and systemic risk. The challenge of translating scientific understanding into economic policy frameworks is compounded by the need to align climate scenarios with socioeconomic development pathways (Riahi et al., 2017; Batibeniz et al., 2023). Different baseline assumptions about population, technology, and governance can create variation in damage estimates comparable to uncertainties in climate sensitivity itself (Rising et al., 2022). This underscores why improving damage functions requires parallel progress in scenario design and socioeconomic modelling. Bringing these communities together to co-design models, share data, and align assumptions is essential if future damage estimates are to be both scientifically credible and practically useful for decision-makers (Tebaldi et al., 2021).

Echoing this finding, the UN's Beyond GDP project evidences an ongoing shift towards measuring sustainable and inclusive well-being. This includes a High-Level Expert Group tasked with broadening the global definition of human wellbeing by 2026, to include inequality, health, natural capital, air and water quality, and greenhouse-gas emissions. Incorporating such indicators would allow climate-damage modelling to align more closely with societal welfare, particularly in cases where GDP understates or hides losses. This matches survey insights showing that experts strongly prefer multi-metric approaches capturing distributional losses, non-market damages, and physical disruption. Even when focusing on GDP, current reporting practices obscure the true severity of impacts. Economists typically report damages as the percentage difference between two hypothetical future GDP levels - with and without climate change - which systematically understates impacts because most of the difference reflects decades of compound growth rather than climate damages. A more transparent approach would report the decline in the rate of economic growth. For example, Kotz et al.'s estimates still predict positive economic growth - just at a rate 0.8 percentage points lower annually. This seemingly modest reduction compounds to the substantial GDP differences reported, but the growth-rate framing makes clearer what climate change does: it acts as a persistent drag on prosperity accumulation. This evidences a **global need for damage modelling to move beyond GDP as its primary economic anchor** (Bastien-Olvera & Moore, 2021). The landmark Stern Review (Stern, 2006) was among the first major economic assessments to emphasize ethical dimensions and distributional concerns, though its damage function approach has since been critiqued for many of the same limitations identified here.

A recent synthesis published (Morris et al., 2025) reinforces many of these findings. The authors show that global GDP-loss estimates for similar warming levels still differ by more than an order of magnitude, from a few percent to over 50 percent, depending on whether models use structural or statistical methods. They argue that reconciling these approaches will require more transparent documentation of assumptions, broader inclusion of overlooked impact channels such as biodiversity loss, migration and conflict, and clearer treatment of adaptation and “fat-tailed” extreme-risk events. This aligns closely with the priorities identified in our workshops: expanding beyond GDP, improving representation of extremes, and integrating cross-sector dynamics. These points directly shape our next-phase work on model development, transparency standards and cross-disciplinary collaboration.

Research on cascading and compounding risks also demonstrates that extreme events propagate through supply chains, credit markets, and infrastructure networks, amplifying damages far beyond the initial physical shock (Lawrence et al., 2020; National Academies, 2024). Financial-sector analyses similarly warn that climate change can generate systemic instabilities, including insurance withdrawal, credit tightening, and macro-financial fragility (BIS, 2020; NGFS, 2022). Climate stress tests reveal transmission channels through which physical and transition risks propagate through financial networks (Battiston et al., 2017, 2021), with recent mapping of global financial exposures highlighting concentrated vulnerabilities (Mandel et al., 2025). Further, asset-level assessments of physical climate risk demonstrate that granular spatial analysis reveals adaptation financing needs that aggregate models systematically underestimate (Bressan et al., 2024). These findings align with critiques of GDP-based damage functions, which overlook distributional losses, persistent economic scarring, and non-market impacts (National Academies, 2017; Hsiang et al., 2017). **Together, this evidence supports the need to move beyond globally averaged,**

smooth damage curves toward modelling frameworks capable of capturing extremes, cascading channels, and dynamic economic responses (Rode et al., 2021).

3.2. Direct improvements to damage functions

Based on expert elicitation results, we present three developments to improve climate damage estimation through refined parameterization of aggregate macroeconomic damage functions. Unlike bottom-up approaches explored in Section 3.3, these developments work within the existing integrated assessment model (IAM) framework, making them more readily implementable in near-term NGFS scenarios. Each development addresses specific limitations identified by climate scientists in our workshops while maintaining computational tractability for policy applications (van Vuuren et al., 2014). In the following subsections, we provide an overview of each development's rationale, approach, and key findings; full technical details, including mathematical formulations, complete statistical results, and methodological specifications, are provided in Appendix A.

Temperature-stratified damage function

Rationale
Current damage functions in IAMs typically assume smooth polynomial relationships between global mean temperature and GDP loss. The most common specification follows Burke et al. (2015) with a quadratic form: damages rise gradually with temperature following a predictable mathematical curve. Here, we test whether expert judgment supports this smoothness assumption by directly eliciting damage estimates at specific warming levels.

Why it matters
Standard functional forms assume continuous, predictable damage accumulation based on extrapolation from limited historical data. Expert judgment can provide calibration targets at policy-relevant temperature levels that lie far outside observed climate conditions, testing whether smooth polynomial relationships adequately capture anticipated impacts or whether non-linearities and thresholds require different specifications.

Approach and results
Rather than fitting mathematical curves to limited historical data, we directly asked climate scientists to estimate economic damages at key policy-relevant temperatures: 1.5°C, 2°C, 3°C, and 4°C, with each temperature level associated with a specific year along a predefined warming trajectory. This approach ensures that damage estimates account for both the temperature level reached and the timeframe over which warming occurs, recognizing that adaptive capacity, technological development, and socioeconomic conditions vary across different time horizons.

These temperature-year combinations provide calibration targets where they matter most for policy decisions.

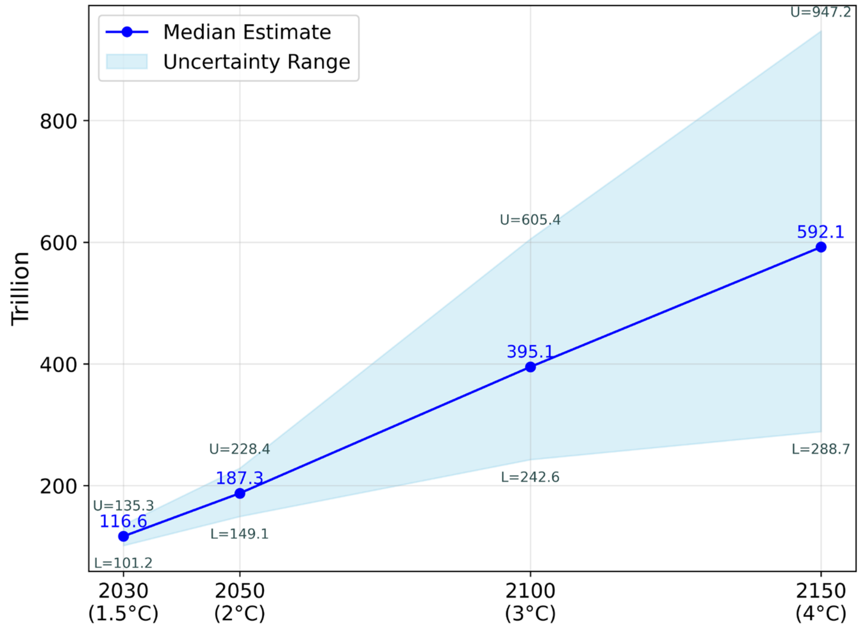

Figure 10. Median estimated damages and uncertainty ranges across warming scenarios.

The results (Figure 10) show that median damage estimates increase more than linearly with temperature, with uncertainty widening dramatically at higher temperatures. At 1.5°C, experts estimate median GDP losses around 10%, while at 3°C this rises to ~35% with much wider uncertainty bands. This contrasts sharply with standard models like Nordhaus DICE, which projects only ~3% GDP loss at 3°C.

The expanding uncertainty reflects expert recognition that as we move beyond observed climate conditions, our ability to predict outcomes diminishes. Current models assume uncertainty stays roughly constant, but expert judgment suggests we become less certain as warming increases - particularly regarding compounding risks, feedback mechanisms, and potential tipping points.

While these estimates draw on the expertise of 68 climate scientists, future work could strengthen robustness by expanding both the sample size and disciplinary scope. Increasing participation would reduce sensitivity to outliers and better characterize uncertainty distributions – a law-of-large-numbers effect particularly valuable for tail risk estimates. Additionally, incorporating climate economists and integrated assessment modelers would enable cross-disciplinary triangulation, revealing where economic modelling assumptions diverge from physical science understanding.

Recommendation

These temperature-stratified estimates can be directly incorporated into NGFS scenarios as alternative damage function calibrations. Rather than selecting a single functional form based on historical data that covers at most 1°C of warming, scenario designers could use expert-elicited values as calibration targets at each key temperature level. This approach acknowledges irreducible uncertainty while providing empirically grounded bounds on economic impacts for financial sector stress testing (Barnett et al., 2020).

Collapse threshold probability distributions

Rationale

Standard damage functions contain an implicit assumption that is rarely examined: economic activity continues indefinitely regardless of temperature. The mathematical forms used in IAMs asymptotically approach 100% damages but never quite reach complete economic collapse. A system might lose 80%, 90%, even 99% of GDP, but it continues functioning at some reduced level no matter how extreme the warming. However, the definition of "economic collapse" is not purely theoretical: a 2024 MSCI survey of financial institutions found that 42–47% of respondents considered total economic loss plausible under extreme climate scenarios (MSCI, 2025). Moreover, it is useful to distinguish between long-term GDP output losses and short-term impacts on financial valuations and wealth, which can be amplified by market volatility and leverage, as seen during crises such as 1929 and 2008. These higher-order financial effects are often overlooked in standard IAMs, highlighting a gap between the metrics familiar to scientists and the risk perspectives used by market participants.

Before examining where collapse thresholds might lie, it is important to recognize what standard damage functions implicitly assume: that economic growth continues indefinitely, merely at reduced rates. Even the most severe damage estimates in conventional IAMs predict positive GDP growth under 3-4°C warming. Climate change appears as a growth-rate reduction - from perhaps 2% annually to 1.2% annually - rather than as absolute economic contraction or system failure. This framing obscures the possibility that at some temperature, the assumption of continued growth itself breaks down. The economy does not simply grow more slowly; it fundamentally cannot function in its current form.

Why it matters

At some level of warming, organized economic activity becomes impossible. Food systems fail, water supplies disappear, cities become uninhabitable, institutions collapse. The question is not whether such a threshold exists, but where it lies and how certain we can be about its location. Eliciting expert views on collapse thresholds provides realistic upper bounds for damage functions and enables tail risk framing familiar to financial institutions.

Approach and results

Here we introduce the concept of an adaptation threshold - a temperature beyond which modern economic and social systems cannot maintain functionality - and uses expert judgment to estimate where this critical point occurs (Kolstad et al., 2014). We asked experts to identify temperature thresholds where they believe modern economic systems could fail. The resulting cumulative distribution (Figure 11) indicates rising risk beyond ~3°C and substantial uncertainty across respondents.

The median collapse threshold occurs at 4°C, but with substantial variation: 36% of respondents identified thresholds below 4°C, suggesting commonly modelled scenarios may venture into territory where economic continuation is questionable. The cumulative probability distribution shows risk accelerating rapidly beyond 3°C, with the sharp rise indicating that most experts cluster their estimates in the 3-5°C range.

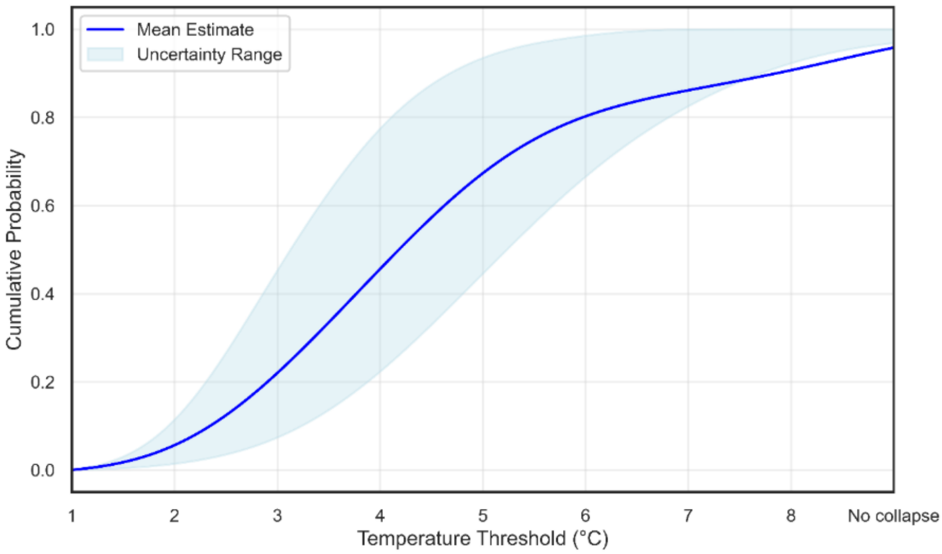

Figure 11. Cumulative probability distribution of estimated temperature thresholds for economic or societal collapse.

A damage function that acknowledges a non-zero probability of complete system failure at high temperatures communicates risk more honestly than one that assumes indefinite continuation with ever-increasing losses. The shape of Figure 11 illustrates why tail risk management must dominate climate strategy. The distribution is notably flat, with 40% of respondents falling outside the 3-6°C range, demonstrating profound uncertainty about collapse thresholds. This uncertainty is precisely why investors and policymakers should manage to avoid the tail rather than optimize for the median. Our current trajectory of 2.7°C under existing policies might appear to provide comfortable margin if the median collapse threshold is 4°C. However, with 36% of experts identifying thresholds below 4°C, this trajectory carries material tail risk of catastrophic outcomes. The tail risk perspective reveals that focusing on "most likely" temperature outcomes—whether 2.7°C or 4°C—induces false comfort. Instead, policy should aim to minimize the probability of crossing any threshold where collapse becomes possible. Given the severe consequences and deep uncertainty about threshold locations, this requires the most aggressive emissions reductions achievable, treating even low-probability catastrophic scenarios as unacceptable risks.

This reframes climate risk in terms familiar to financial institutions: tail risk and probability of default. Rather than assuming indefinite adaptation, it acknowledges hard physical limits and provides realistic upper bounds for damage projections. The implications for functional form selection are significant. Standard quadratic or cubic polynomials cannot represent collapse thresholds - they grow smoothly without bound. Alternative forms are needed. Logistic functions saturate at 100% damages, providing a natural upper bound. Weitzman-style specifications with singularities at a critical temperature explicitly incorporate collapse thresholds. Piecewise functions can show sharply accelerating damages beyond a threshold temperature. We explore different functional forms in the next section.

Recommendation
Collapse threshold distributions can be used to constrain the upper bounds of damage functions in IAMs, preventing unrealistic assumptions about indefinite economic continuation at extreme temperatures. This provides a natural ceiling for damage projections and forces explicit consideration of system limits. Financial institutions can use these probability distributions to assess tail risk exposure in high-warming scenarios, translating climate science into familiar Value-at-Risk frameworks.

It must be acknowledged that this remains exploratory. The concept of "economic collapse" is not precisely defined, and expert interpretations varied. Some respondents focused on physical survival limits - temperatures that preclude outdoor human activity or food production. Others emphasized institutional breakdown - the point where governance, trade, and coordinated adaptation become impossible. Still others considered technological possibilities, arguing that sufficient innovation could extend adaptation capacity beyond any specific temperature threshold (Deschênes & Greenstone, 2011; Heutel et al., 2021).

Despite these ambiguities, the exercise serves an important purpose. It makes explicit an assumption that IAMs embed implicitly: can economic systems continue indefinitely, or do hard limits exist? By forcing this question into the open and eliciting expert judgment about where limits might lie, we provide a reality check on damage function extrapolation. Scenarios that venture beyond the median collapse threshold should be treated with appropriate caution, recognizing that they may represent conditions beyond which economic modelling becomes meaningless. This is particularly relevant for long-term investors, such as pension funds with a 40-year planning horizon, for whom scenarios beyond ~3 °C of warming may already involve uncertainties so large that projections become highly unreliable.

Functional form comparison

Rationale
The mathematical function chosen to represent the temperature-damage relationship has profound implications for estimated impacts, yet this choice is

typically made on grounds of computational convenience rather than empirical fit. The quadratic form dominates integrated assessment models not because data strongly support it – but because it is simple, tractable, and consistent with economic intuition about diminishing marginal productivity. However, climate damages are fundamentally a physical and biological problem, not an economic one. The correct functional form should emerge from aggregating impacts on crops, ecosystems, infrastructure, and human health - not from assumptions about how economic systems respond to generic shocks. Different functional forms produce dramatically different damage estimates at policy-relevant temperatures. At 3°C warming, the difference between moderate and catastrophic damage specifications can exceed an order of magnitude - making functional form choice critical for policy scenarios exploring 2-4°C warming.

Why it matters

Complex systems do not necessarily fail gradually. While the quadratic form assumes smooth, continuously increasing damages, empirical evidence from ecosystems, infrastructure networks, and human societies suggests the possibility of threshold effects, accelerating feedbacks, and system-wide collapses. Power laws capture accelerating nonlinear responses; logistic and Weibull functions represent systems approaching capacity limits; exponential forms reflect compounding feedback processes. Each functional form embeds different assumptions about how Earth systems respond to temperature stress - assumptions that cannot be validated within the narrow range of observed warming (0.2-1.0°C) but become critical when extrapolating to 3-4°C. The functional form debate is not merely technical - it is fundamentally about whether we expect climate impacts to remain manageable and incremental, or whether we anticipate the possibility of cascading failures and regime shifts in coupled human-natural systems (Kikstra et al., 2021).

Approach and results

We tested seven mathematical specifications (quadratic, exponential, power law, logistic, Gompertz, polynomial, and Weibull) against both historical disaster data and expert collapse thresholds. Within the narrow observed temperature range (0.2-1.0°C), all functions fit equally well (Figure 12, left panel). When extrapolated to policy-relevant temperatures like 3°C, they diverge dramatically (Figure 13).

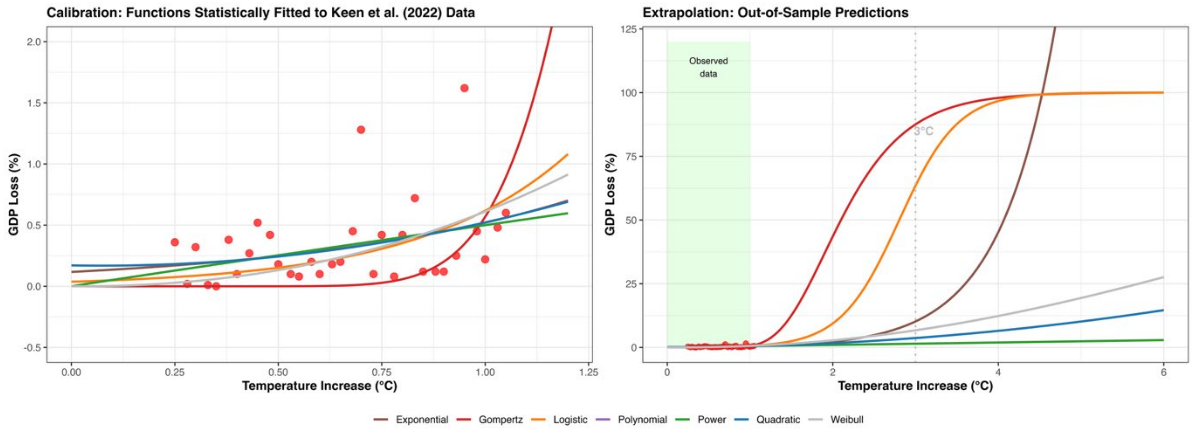

Figure 12. Various functional forms fitted to observed damages

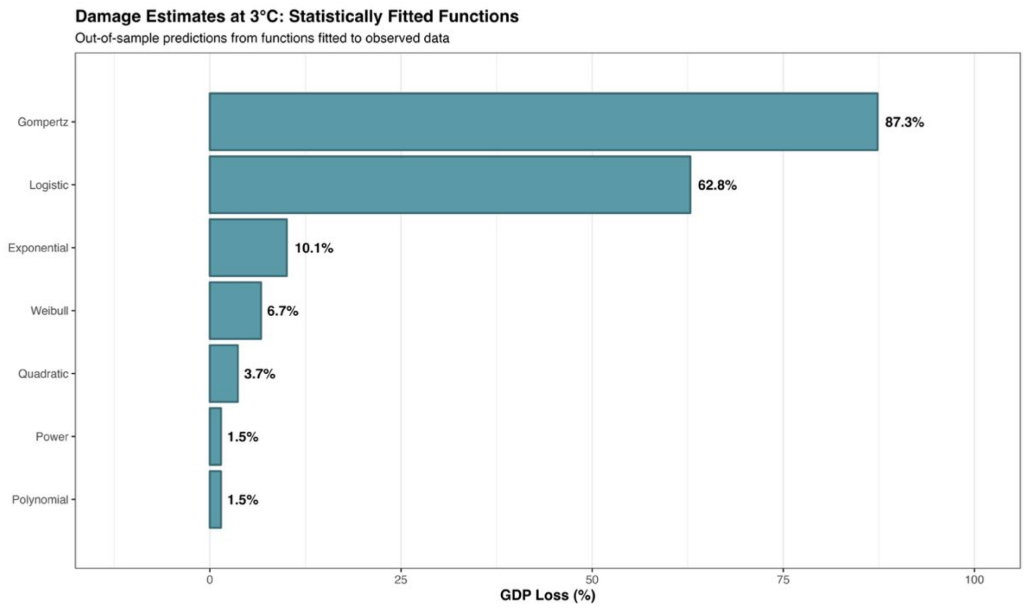

Figure 13. Loss at 3 degrees warming resulting from different functional forms fit to observed damages (as shown in Figure 12).

Importantly, not all functions can satisfy both constraints: very early collapse scenarios (below 2.7°C) are incompatible with historical observations, while smooth polynomial forms that fit the data produce unrealistically low damages at high temperatures. Power and polynomial forms suggest 3°C warming would cause less than 4% GDP loss - inconsistent with expert understanding of climate impacts and physical evidence of system thresholds. By constraining each function to reach 100% economic loss at expert-identified collapse thresholds, we generate an ensemble of plausible damage trajectories (Figure 14).

-

“Power and polynomial forms suggest 3°C warming would cause less than 4% GDP loss - inconsistent with expert understanding of climate impacts and physical evidence of system thresholds.”

-

Recommendation

The solution is an ensemble approach: rather than selecting a single "best" function, we report the full range of plausible outcomes. At 3°C, compatible damage estimates span 44-88% of GDP using median collapse thresholds. This uncertainty is not a flaw in the analysis - it reflects genuine structural uncertainty about how Earth systems respond to unprecedented warming.

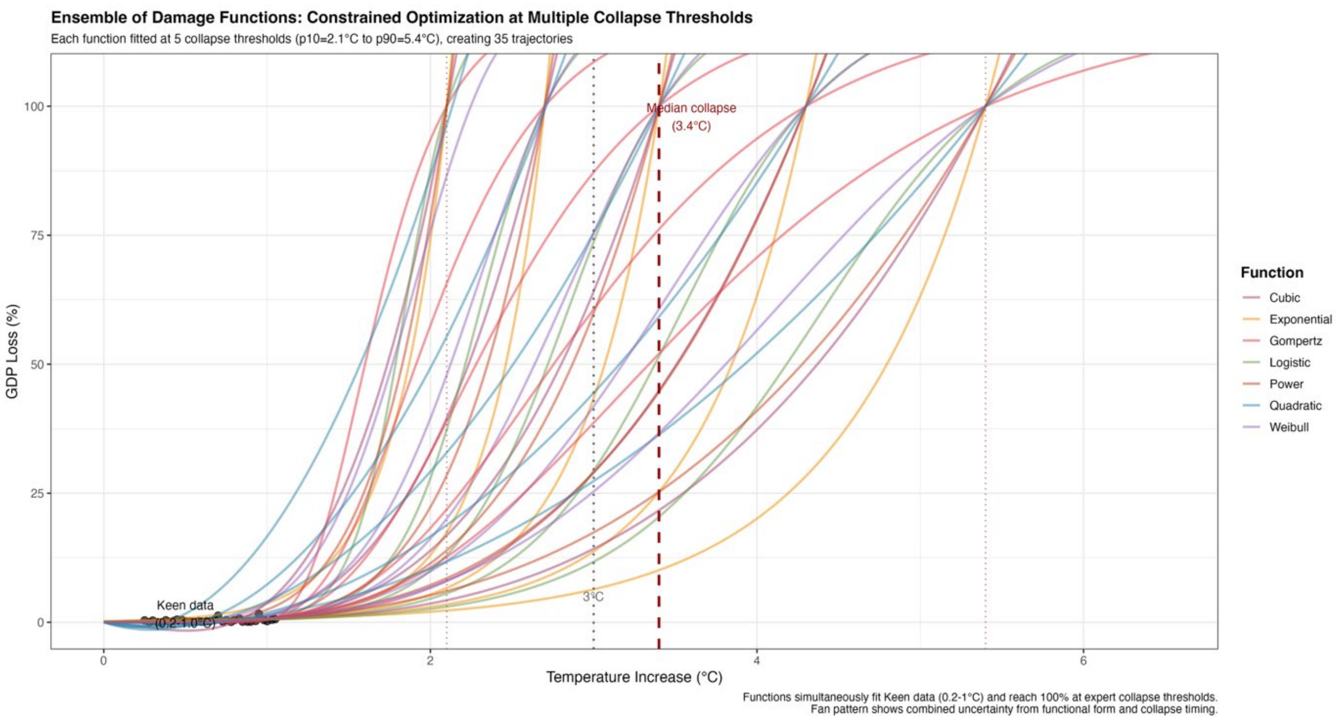

Figure 14. Ensemble of damage functions generated through constrained optimization. Each function is fitted at five different expert collapse thresholds, creating a fan pattern that shows combined uncertainty from functional form choice and collapse timing. All trajectories pass through Keen disaster observations (0.2-1.0°C) while approaching 100% loss at their respective collapse thresholds. The vertical dashed line marks the median collapse threshold (3.4°C).

The wide divergence between functional forms is not a failure of the method but a revelation of genuine structural uncertainty. Current integrated assessment models make a strong implicit bet by universally adopting quadratic specifications, assuming Earth systems will respond to 3-4°C of unprecedented warming in the same smooth, manageable way they responded to 1°C. This assumption lacks physical justification and is contradicted by evidence of threshold effects, tipping points, and nonlinear responses in climate subsystems. When damage estimates at policy-relevant temperatures vary by factors of 2-14 depending on defensible functional form and collapse threshold choices, decisions must be robust across this range rather than optimized for a single "best guess."

-

Current integrated assessment models make a strong implicit bet, assuming Earth systems will respond to 3-4°C of unprecedented warming in the same smooth, manageable way they responded to 1°C.

-

The ensemble acknowledges what we know (disasters correlate with temperature, collapse occurs somewhere between 2-6°C) and what we do not (the precise mathematical relationship, the exact collapse threshold). This quantification of uncertainty should inform, not paralyze, climate action - revealing that the range of plausible outcomes spans from serious economic disruption to near-total collapse. It reinforces the precautionary principle - delaying action risks encountering extreme outcomes; for adaptation, it cautions against relying on a single scenario or “best guess” and instead encourages planning across a plausible range or band of outcomes, avoiding the trap of false precision that has led some advisors to exclude tipping points from official scenarios.

Synthesis

Rather than implementing these three developments separately, we combine them into a unified Expert-Calibrated Damage Function that synthesizes expert judgment across multiple dimensions. This probabilistic framework uses temperature-stratified estimates as calibration targets, respects collapse threshold distributions as upper bounds, and weights multiple functional forms based on how well they capture expert understanding.

The ECDF offers key advantages: explicit transparency in assumptions, proper uncertainty quantification, and systematic incorporation of expert knowledge. For NGFS scenarios and financial stress testing, it provides the full distribution of potential outcomes rather than misleading point estimates.

However, these aggregate damage functions - no matter how sophisticated - still suffer from the top-down limitations workshop participants identified. Section 3.3 explores complementary bottom-up approaches that capture mechanisms invisible to aggregate functions: capital destruction, sectoral dynamics, extreme event volatility, and adaptation limits.

3.3. Indirect improvements to climate damage modelling – *alongside* damage functions

The survey-based developments in Section 3.2 represent substantial improvements that can be implemented immediately within existing integrated assessment models - providing better calibration, capturing nonlinearities, and acknowledging collapse risks. These developments address critical gaps identified by climate scientists and can inform NGFS scenarios within months. However, workshop participants emphasized that temperature-GDP relationships, even with these improvements, cannot fully capture all mechanisms through which climate impacts manifest. They called for complementary "process-based or system-dynamics approaches, where GDP is an outcome that emerges from all the interacting systems" rather than being directly modelled. Section 3.3 therefore presents bottom-up analyses that work alongside - not instead of - aggregate damage functions.

The following developments complement aggregate damage functions by providing granular analysis of specific impact channels that cannot be adequately captured in macroeconomic relationships. These address the highest priorities from expert elicitation: integrating alternative climate metrics beyond mean temperature, better integration of tipping points and cascading effects, improved representation of extreme events, and issues around temporal and spatial scales and resolution (Cruz & Rossi-Hansberg, 2024).

Unlike Section 3.2's survey-based developments, the analyses presented here are theoretical illustrations using defensible but not empirically calibrated parameters. Their purpose is to demonstrate *how* specific mechanisms could be modelled and *why* they matter for damage estimation, not to provide definitive quantitative estimates. They represent a research agenda showing where current approaches fall short and what improvements are needed.

Rather than replacing damage functions, these approaches could inform better parameterization of aggregate relationships or operate alongside them in NGFS scenarios. The guiding questions are: How might these systemic risks be brought into NGFS scenarios, if not through damage functions? Can they be incorporated into damage functions at all?

Adequacy of GDP and alternative progress metrics

Rationale

Workshop participants questioned whether GDP is the right metric. It often leads to perverse outcomes: *natural disasters often increase GDP, so it's not what we really want to measure* (Costanza et al., 2014). Beyond the GDP paradox (reconstruction spending counted as growth), GDP misses health burdens, ecosystem degradation, inequality, and wellbeing. Alternative metrics like Gini coefficient, Genuine Progress

Indicator, and Human Development Index could provide more comprehensive climate impact assessment. A majority of respondents who consider GDP inadequate highlight the need for metrics that capture inequality, distributional losses, non-market damages, and physical destruction, dimensions routinely missed in GDP-centred approaches. This complements the workshop view that economic damages should reflect human wellbeing, structural change, and system-wide fragility rather than changes in aggregate output alone (Carleton et al., 2022; Bressler, 2021).

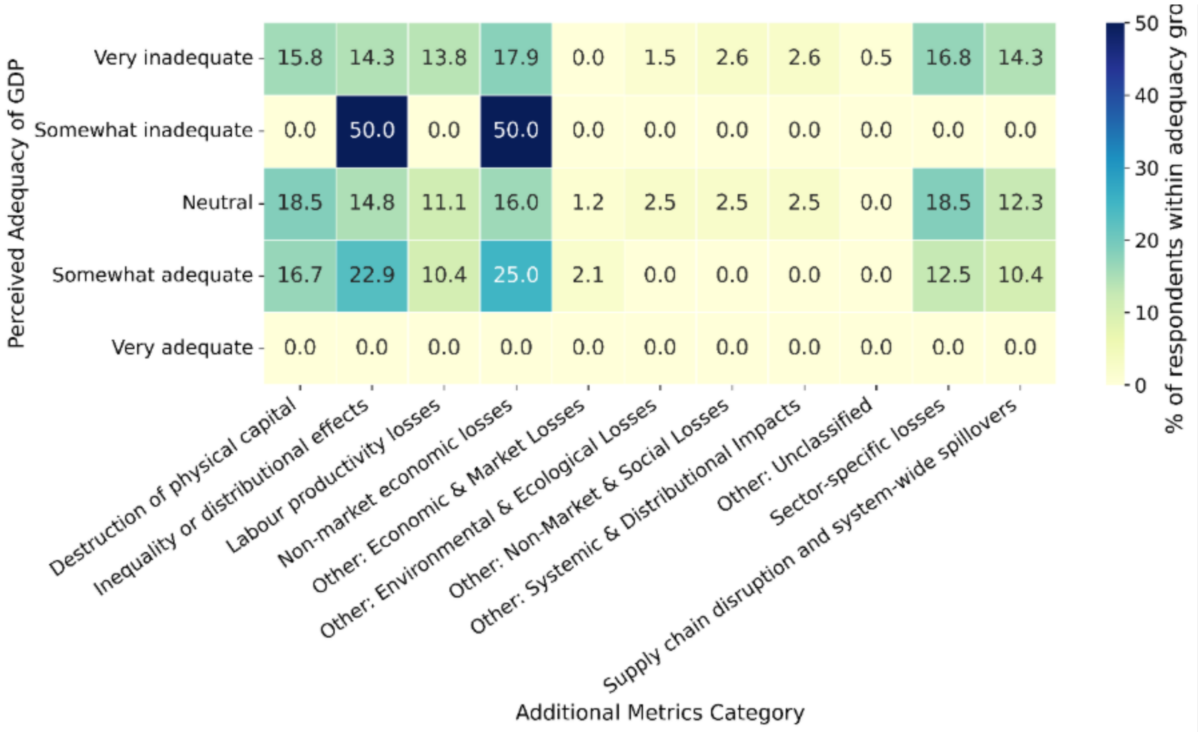

Figure 15. Perceived adequacy of GDP and expert-identified additional metrics.

Why it matters

Different damage pathways and measurement frameworks reveal impacts that GDP obscures. Climate change worsens inequality (Gini), degrades environmental quality (GPI), reduces life expectancy and education access (HDI), and causes direct mortality (deaths from heat and extreme events). These non-GDP metrics complement economic damages and avoid the measurement problem where disaster recovery inflates GDP while genuine prosperity declines (see, for example, the Bloomberg 'Prepare and Repair Index' which is outperforming the S&P 500).

Approach and results

Regional heterogeneity in impacts (5x range) illustrates how warming exacerbates inequality - the Gini coefficient rises as low-income regions suffer 49% losses while high-income regions experience only 10%. This pattern reflects a combination of factors: lower adaptive capacity in many Global South regions, greater exposure of vulnerable populations, and assumptions embedded in models about resource availability and resilience, rather than uniform climate sensitivity. Notably, some high-income regions, such as Europe, are warming faster than the global average, highlighting that the pattern is not purely latitudinal. For mortality, direct deaths from heat stress and extreme events can be quantified rather than converted to GDP equivalents, avoiding the measurement problem (Burke et al., 2023; Matthews et al., 2025; Falchetta et al., 2024). Given the limited involvement of Global South experts in some studies, further expert elicitation would be valuable to avoid assumptions that high impacts are concentrated in the Global South and that the Global North is shielded. Health burden in DALYs captures impacts GDP misses. HDI components show climate affecting life expectancy, education access, and income simultaneously, while GPI accounts for environmental degradation and inequality alongside consumption. Reconstruction spending may boost GDP - as documented by the BBG Prepare and Repair index for the U.S., where an increasing share of economic activity is associated with such spending (already ~1/3 at 1.4 °C warming) - this is not necessarily an indicator of a healthy economy, as it may reflect reactive expenditures rather than genuine prosperity (Ricke et al., 2018).

Recommendation

Scenarios should report climate impacts across multiple metrics, rather than relying on GDP alone. While participants acknowledged that GDP remains a practical and widely used benchmark in financial analysis - particularly for investors modelling revenues in cyclical sectors - it is insufficient as a standalone measure of climate damage, as it captures spending flows rather than underlying economic health. Near-term implementation could therefore complement GDP with distributional metrics such as Gini coefficients, direct mortality estimates from heat and extremes, health burdens measured in DALYs, and changes in HDI components. Medium-term development could incorporate measures such as GPI, which account for environmental degradation and inequality alongside consumption. This broader approach frames “damage” as the value of lost assets, lost lives, and the cost of rebuilding - remaining economically interpretable while avoiding the GDP measurement problem - and represents a research agenda requiring consensus on which non-GDP metrics are most policy-relevant.

Process-based economic transmission channels

Rationale

Current damage functions relate temperature directly to GDP output, treating climate change as a productivity shock. However, you don't actually damage output (GDP) - you damage capital stock, labour productivity, and infrastructure, which then impact output. Workshop participants emphasized the need for process-based approaches where GDP emerges from interacting systems rather than being directly modelled.

Why it matters

An important issue highlighted by recent work is that natural disasters often increase measured GDP because disaster recovery spending counts as economic activity - the disaster industrial complex has become a huge part of the US economy. This means standard damage functions systematically underestimate true losses by measuring spending flows rather than wealth stocks. Process-based modelling of capital destruction, labour impacts, and productivity losses provides a more accurate picture of economic damages (Zhang et al., 2018).

Approach and results

We developed a theoretical model to illustrate transmission mechanisms.
Three channels were modelled:

- **capital destruction** from extreme events ($D_K = 0.5 \times D_{GDP} \times K_t$)
- **labour productivity losses** affecting 50% of the economy
- **TFP degradation** ($A_{t+1} = A_t(1 + g_A)(1 - 0.3 \times D_{GDP})$)

Standard economic parameters were used (α=0.33, δ=0.05, s=0.20). At 3°C with baseline damage function $D(T) = 0.02T + 0.015T^2$, direct GDP losses reach 19.5%. Transmission mechanisms amplify this: capital channel to 42.6% (2.2x), adding labour to 61.1% (3.1x), and combined to 97.7% (5.0x). These multipliers illustrate how modest annual effects compound through feedback loops over 80 years.

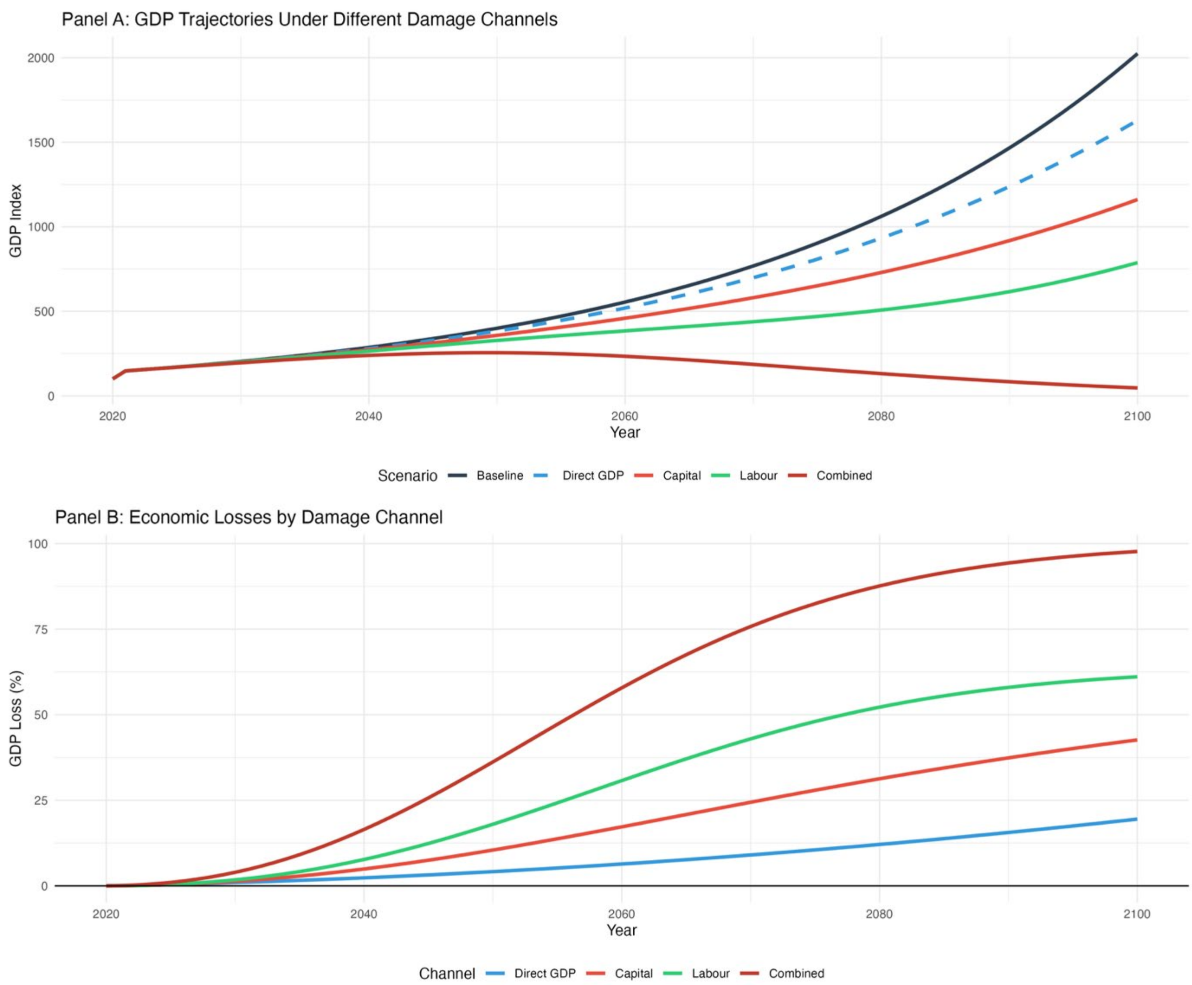

Figure 16. Economic transmission amplifies climate damages through feedback loops

It is important to note that these amplification factors are theoretical illustrations using defensible parameters from growth literature, not empirically calibrated to climate impacts. The purpose is demonstrating that transmission mechanisms *exist* and *matter*, not providing precise multipliers for policy use. Empirical calibration would require historical data on climate-induced capital destruction and productivity losses currently unavailable at the scales modelled (Lemoine & Rudik, 2017).

Recommendation
This development demonstrates that process-based channels should inform damage function parameterization. Near-term implementation could involve multiplying standard damage functions by amplification factors derived from transmission analysis. Medium-term integration would explicitly model capital, labour, and TFP channels. The key insight is that measuring "damage" as value of lost assets and capital stock, rather than just GDP impacts, provides more accurate economic risk assessment.

Extreme events and stochastic shocks

Rationale
Workshop participants emphasized: *what people actually experience are local extremes, not global averages*. Standard damage functions based on mean temperature miss the fact that extreme events drive much of actual damage. Probabilistic changes in frequency and intensity of extremes at different warming levels create volatility that smooth curves cannot capture.

Why it matters
This directly addresses Priority #3 (extreme events representation). Volatility creates welfare losses beyond mean damages through irreversibility (destroyed capital cannot be instantly rebuilt), adaptation constraints (rapid shocks overwhelm response systems), and financial instability (sudden losses trigger cascading failures). The economic cost of volatility could add 20-30% to mean damage estimates even when average impacts are identical.

Approach and results
We used Monte Carlo sampling to illustrate stochastic dynamics. Events occur with probability $p(T) = 0.02 + 0.06T$ and magnitude scaling with temperature. Extreme weather creates cascading impacts through energy markets and supply chains (Reith et al., 2024). The smooth mean trajectory shows 19.5% loss by 2100 at 3°C. Stochastic realization shows the same mean but with spikes to 30-45% in event years. These parameters are illustrative, not empirically calibrated to specific hazards. The analysis demonstrates the *concept* of volatility around mean trajectories and why it matters for welfare, not precise probability distributions for policy use. Operational implementation would require calibration to physical climate models and historical event data.

Recommendation

NGFS scenarios should incorporate stochastic extreme event overlays using physical risk hazard data. Near-term implementation involves running Monte Carlo ensembles with temperature-dependent event probabilities and reporting percentile ranges (10th, 50th, 90th) rather than means alone. Sectoral damage functions could map specific hazards (flooding, wildfire, storms) to infrastructure, agriculture, and mortality impacts. The key is maintaining transparency about which events drive aggregate damages rather than obscuring volatility in smooth curves.

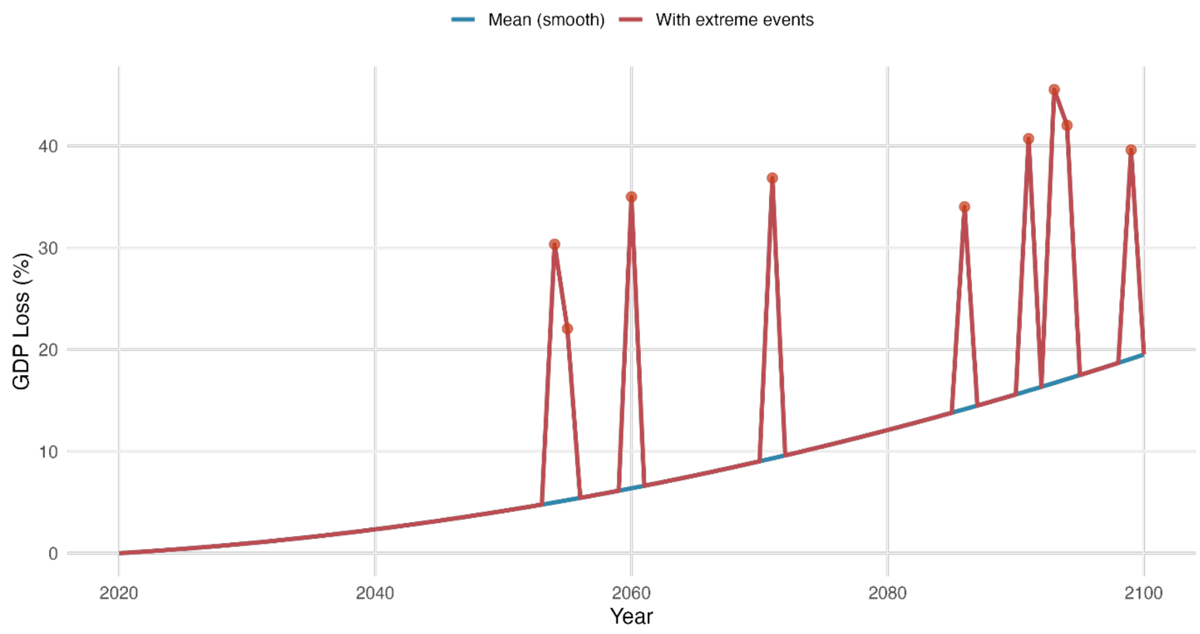

Figure 17. Extreme events create volatility around smooth mean trajectories

Tipping Points and nonlinear dynamics

Rationale

Workshop participants emphasized that climate systems "don't behave smoothly; they shift suddenly once thresholds are crossed." Standard polynomial damage functions cannot represent tipping point risks such as Amazon forest dieback, permafrost melt, ice sheet disintegration, and ocean circulation disruption. These create acceleration of warming through Earth system feedbacks plus catastrophic regional impacts that smooth curves miss entirely (Steffen et al., 2018; Rockström et al., 2023 ; Wunderling et al., 2023).

Experts identify low to moderate temperature thresholds for several tipping-point categories, particularly coral and ocean-ecology collapse (~1.5–2°C) and biosphere disruption (~2–3°C). The wide uncertainty ranges for cryosphere, circulation, and system-wide tipping events highlight deep epistemic uncertainty and align with the view that damages may escalate abruptly when thresholds are crossed. These results reinforce calls to explicitly model threshold dynamics and non-smooth responses.

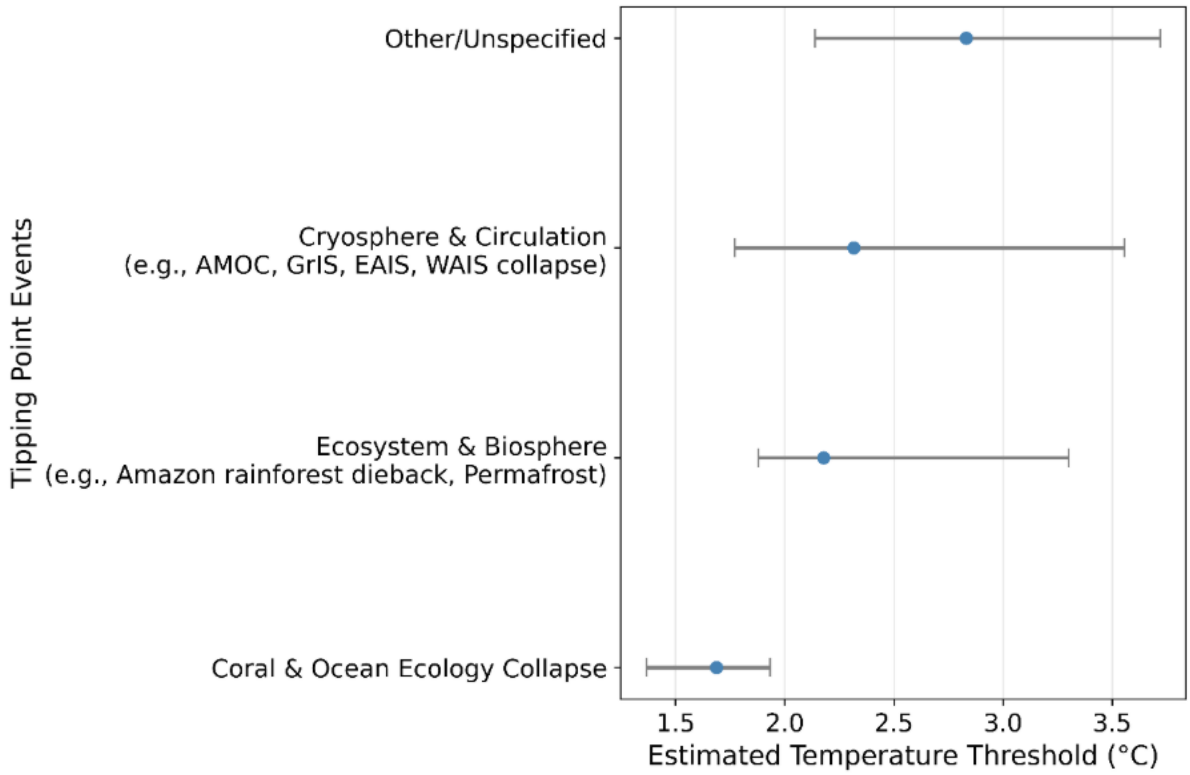

Figure 18. Estimated temperature thresholds for major tipping-point categories.

Why it matters

This directly addresses Priority #2 (tipping points integration). Tipping points create discontinuous jumps in damages at critical temperature thresholds. Recent synthesis (Armstrong McKay et al., 2022, Lenton et al., 2025) identifies multiple tipping elements becoming probable in the 1.5-3°C range - precisely where policy-relevant scenarios operate. Failure to represent these dynamics means IAMs systematically underestimate tail risks (Kopp et al., 2016).

Approach and results

We compared seven functional forms: quadratic (19.5% at 3°C), exponential (9.3%), piecewise (35.0%), logistic (69.5%), power law (57.8%), Weibull (33.6%), and tipping points (59.5%). The 7.5x range demonstrates fundamental structural uncertainty. The tipping points form includes jumps at coral reefs (1.5°C, +5%), Amazon dieback (2.0°C, +8%), ice sheets (2.5°C, +12%), and AMOC (3.0°C, +15%) (Yumashev et al., 2019).

Again, it is important to note that all functional forms presented here are theoretical constructs, not empirically validated at 3°C. Tipping point magnitudes (+5% to +15%) are illustrative estimates consistent with Earth system literature, not precise impact assessments. The analysis demonstrates *that* functional form choice matters enormously and *how* to represent threshold dynamics, not which form is "correct."

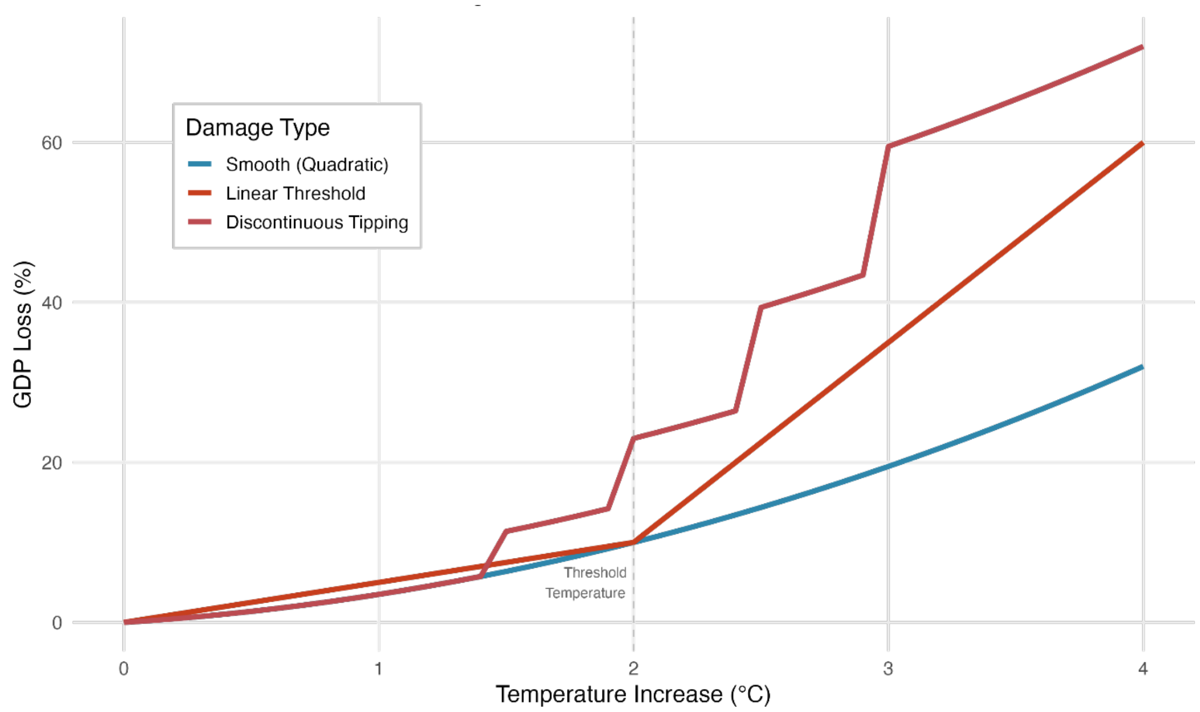

Figure 19. Tipping point dynamics fundamentally change damage trajectory

Recommendation

Tipping points could be incorporated into NGFS scenarios through multiple approaches. In the first instance, they could be included as acceleration of warming from Earth system feedbacks (Amazon, permafrost), modifying temperature trajectories in climate models. Additionally, discontinuous damage functions with jumps at critical thresholds could replace smooth polynomials. Narrative scenarios could trace how crossing one tipping point triggers cascading impacts - the security blindspot approach showing systemic risk propagation. Near-term implementation involves sensitivity analysis using tipping points functional forms. Medium-term integration would link to Earth system models, switching from smooth to discontinuous forms when physical indicators suggest approaching thresholds (Lenton et al., 2019; Lontzek et al., 2015; Steffen et al., 2018; Rockström et al., 2023; Knutti et al., 2017; Tebaldi et al., 2021).

Spatial and temporal scales, resolution, and (dis)aggregation

Rationale

Workshop participants called for "starting from the bottom up, using data at grid-cell or regional levels... diversity of local impacts isn't lost in averaging." Survey responses widely highlighted that oversimplified temporal dynamics and limited spatial resolution are critical limitations of current damage functions. Aggregate damage functions obscure critical heterogeneity across multiple scales. Spatial aggregation from grid-cell to global hides vastly different regional and sectoral experiences.

Temporal aggregation from daily or seasonal to annual averages treats slow-onset changes (sea level rise, soil degradation) identically to sudden shocks (hurricanes, heat waves). Scale matters fundamentally—what happens locally and when it happens determines actual impacts on people, ecosystems, and economies.

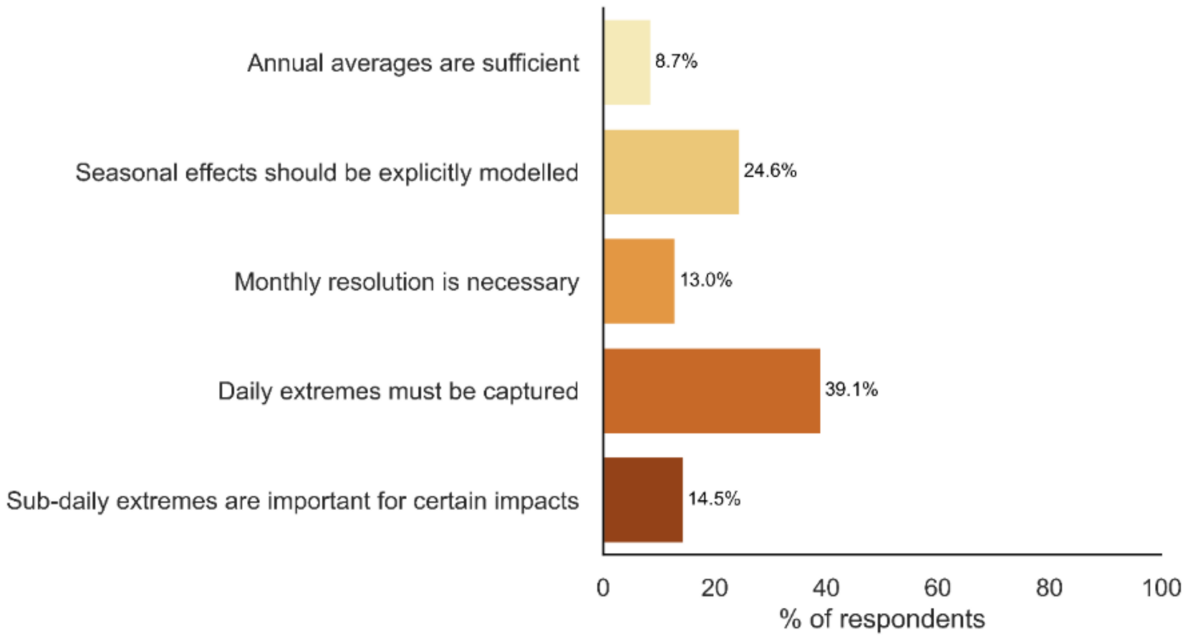

Figure 20. Temporal resolution experts believe should be incorporated in damage functions.

Only 9% of respondents believe annual averages are sufficient. Most highlight the need to model daily or even sub-daily extremes, while nearly 40% prioritise daily temperature and precipitation variability. This highlights the inadequacy of annual-mean temperature as the primary climate input and supports the shift toward models that capture short-duration extremes and seasonal patterns.

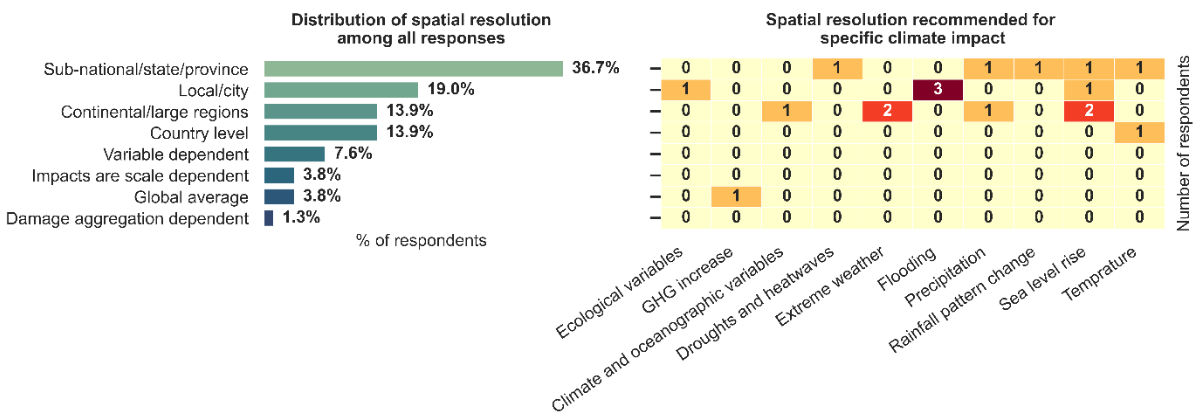

Figure 21. Preferred spatial resolution for climate damage estimation.

Respondents strongly favour sub-national and local spatial scales over national or global averages, reflecting the highly uneven and geographically clustered nature of climate impacts. The accompanying heatmap shows that different climate hazards require different spatial resolutions. For instance, flooding and heatwaves demand city- or state-scale data, whereas GHG concentrations can be assessed at broader scales. This reinforces the need for models that can operate across multiple spatial layers.

Why it matters

This directly responds to widespread concerns about oversimplified temporal dynamics and limited spatial resolution in current damage functions. Survey respondents emphasized that aggregation across space and time obscures the actual experience of climate impacts. Impacts vary enormously by spatial scale (global vs regional vs grid-cell, economic sectors, rural vs urban), temporal scale (annual averages vs seasonal extremes, gradual vs abrupt changes, near-term vs long-term), and organizational scale (households vs firms vs nations). Even if global annual averages appear moderate, catastrophic damages concentrated on vulnerable populations, specific seasons, or particular locations create humanitarian crises that aggregate functions miss entirely.

Approach and results

The following disaggregation examples are illustrative, not empirically calibrated. The analysis demonstrates *that* scale matters enormously and *how* to structure multi-scale analysis, not precise disaggregated damage estimates. Operational use requires calibration to scale-specific impact models.

Spatial heterogeneity: We illustrate with regional disaggregation (high/middle/low-income: 10%, 23%, 49% at 3°C—**5x range**) and sectoral disaggregation (agriculture/manufacturing/services/digital: 78%, 29%, 16%, 4%—**20x range**). Dynamic spatial equilibrium approaches can capture these heterogeneous impacts (Rudik et al., 2023).

Temporal heterogeneity: Damage functions use annual averages, missing seasonal variation (agricultural growing seasons, monsoon dependence), multi-year cycles (El Niño impacts), and distinction between gradual trends (slow capital depreciation) versus sudden shocks (hurricane destroys infrastructure overnight).

Organizational heterogeneity: Households experience different impacts than firms, small firms different than large, nations different than subnational regions. A climate shock simultaneously affects individual farmers (crop loss), agricultural firms (supply disruption), food processing industry (input shortages), national food security (price spikes), and international trade (export reductions). Single aggregate functions cannot capture this multi-scale cascade.

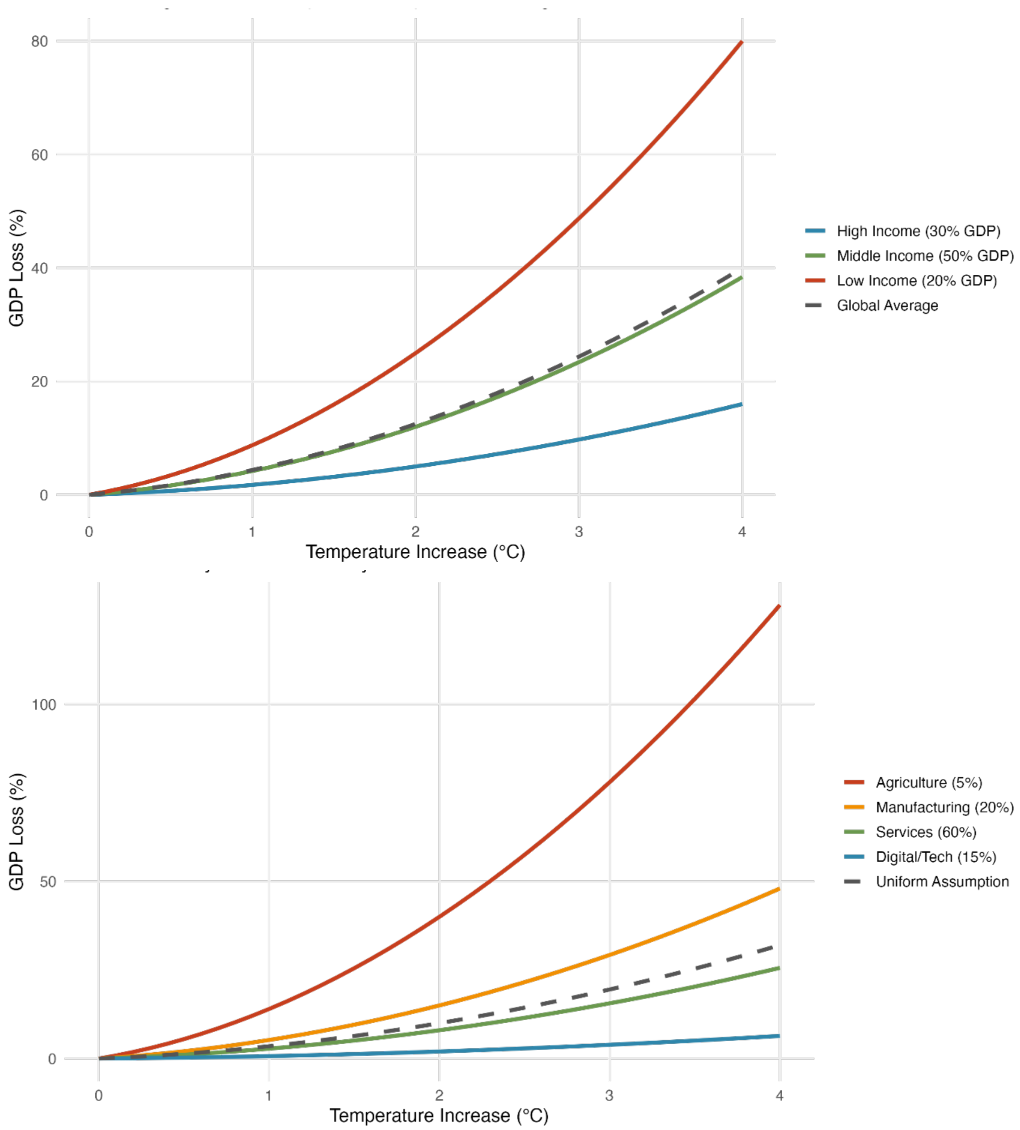

Figure 22. Regional (top) and sectoral (bottom) heterogeneity

Recommendation

Bottom-up, scale-explicit approaches should complement top-down damage functions. **Spatial scales:** Near-term disaggregation by region and sector; medium-term grid-cell resolution with sector-specific functions; long-term household/firm-level analysis linked to macro-outcomes. **Temporal scales:** Distinguish slow-onset (sea level, soil, glaciers) from rapid-onset (storms, floods, heat waves); model seasonal impacts (growing seasons, monsoons); separate decadal trends from interannual variability. **Organizational scales:** Track impacts at household, firm, subnational, and national levels showing how local shocks aggregate to macro-outcomes. The key is not losing critical heterogeneity through premature averaging across scales.

Section 4: Summary and Recommendations

This survey results demonstrate a fundamental disconnect between what climate scientists understand about climate impacts and how these impacts are represented in economic models. Expert elicitation reveals deep concerns about oversimplified temporal dynamics, limited spatial resolution, inadequate treatment of tipping points, and the failure to capture extreme events and cascading risks. Addressing these limitations requires research investments spanning years, yet the window for preventing catastrophic warming is narrower - underscoring that policy action cannot await perfected models but must proceed on the basis of precautionary risk management, physical climate science, and observed impacts.

4.1. Key findings: a fundamental disconnect

The gap is real and consequential
Survey responses reveal that climate scientists view current damage functions as fundamentally inadequate. Respondents highlighted that approaches remain overly top-down and GDP-centred, with limited capacity to represent the local, sector-specific, and cumulative nature of losses. The reliance on smooth polynomial relationships between global mean temperature and aggregate GDP obscures the mechanisms through which climate impacts actually manifest: through destroyed capital stock, degraded labour productivity, disrupted supply chains, and cascading system failures.

Several respondents urged replacing GDP-based "black box" functions with non-GDP-centred frameworks that integrate multiple dimensions of welfare, inequality, and human security. The GDP measurement problem is particularly acute: natural disasters often increase measured GDP through reconstruction spending while genuine prosperity declines. This systematic bias means econometric calibration to historical data will perpetuate underestimation.

Scale and heterogeneity matter fundamentally
Respondents consistently emphasized that oversimplified temporal dynamics and limited spatial resolution are critical limitations. Survey responses called for bottom-up, process-based models at appropriate spatial scales - grid-cell or regional rather than global averages - and with temporal resolution distinguishing seasonal impacts, gradual versus abrupt changes, and slow-onset versus rapid-onset hazards. The distributional consequences are particularly concerning. Even if global GDP losses appear moderate, catastrophic damages concentrated on vulnerable populations create humanitarian crises, migration pressures, and security threats that aggregate functions entirely miss. This reveals a critical feedback loop: first-round effects on GDP may seem manageable in aggregate, but by failing to capture capital destruction, labour productivity losses, ecosystem degradation, and institutional breakdown,

standard models miss the devastating second-round effects. These cascading impacts - supply chain failures, credit market stress, insurance withdrawal, and governance collapse - amplify initial shocks far beyond what aggregate GDP metrics suggest, transforming seemingly moderate first-round impacts into compounding economic crises.

Current approaches underestimate compounding risks

Respondents also emphasised that effective models must distinguish between impacts on physical systems and on the social fabric, recognising that systemic and compounding social risks - including the breakdown of networks, migration cascades, and political fragility - often drive the most severe damages.

The theoretical analyses in Section 3.3 illustrate why standard approaches likely underestimate substantially. Economic transmission mechanisms through capital destruction, labour productivity losses, and innovation slowdown create compounding effects that aggregate functions miss. Adaptation assumptions ignore declining effectiveness, explicit costs, and capacity constraints. Functional form choices - smooth polynomials versus threshold dynamics - create order-of-magnitude divergence at high temperatures yet are typically made for mathematical convenience rather than physical reasoning. Extreme event volatility produces welfare losses that smooth mean-temperature trajectories cannot capture. Taken together, these represent structural uncertainty reflecting disagreement about mechanisms, not parameter uncertainty amenable to measurement. Different defensible modelling choices create ranges spanning factors of several times to an order of magnitude at policy-relevant warming levels, meaning robust decision-making is essential when structural choices dominate outcomes.

A paradigm shift is needed

Overall, the survey calls for a paradigm shift - moving from deterministic, GDP-centred models toward pluralistic, socially contextualized, and reflexive frameworks that represent the intertwined physical, financial, and institutional pathways of climate risk. Respondents criticized the epistemological rigidity of prevailing paradigms - particularly their physicalist and reductive economic foundations – and called for stronger cross-field collaboration among economists, climate scientists, social scientists, financial analysts, economic advisory agencies, fiscal policymakers, and health experts.

Crucially, this paradigm shift must include reframing climate risk from 'most likely outcome' to ‘risk management,' following actuarial best practice in treating low-probability, high-impact events. Building consensus around specific temperature thresholds (e.g., 4°C) as points of ruin enables setting policies to eliminate rather than merely reduce the probability of such outcomes.

Participants stressed that model scale and purpose must align: while global frameworks are useful for conceptual exploration, policy relevance requires finer regional or sectoral resolution, supported by empirical calibration and high-resolution socioeconomic data. Some expressed scepticism about the continued reliance on expert elicitations and objective-probability approaches, advocating the use of qualitative and visual methods for communicating uncertainty, consistent with the Moss and Schneider (2000) framework adopted by the IPCC.

4.2. Recommendations:

Recommended Research to Improve Damage Modelling

Looking ahead, responses outlined a clear research agenda. Experts called for greater integration of political, geopolitical, and societal dynamics into climate damage modelling, deeper connections between empirical evidence and complex-systems analysis, and a new generation of interdisciplinary "handshake" frameworks linking Earth-system and socioeconomic models. They also urged that modelling communities amplify heterodox and cross-disciplinary perspectives to better capture social, ecological, and economic heterogeneities.

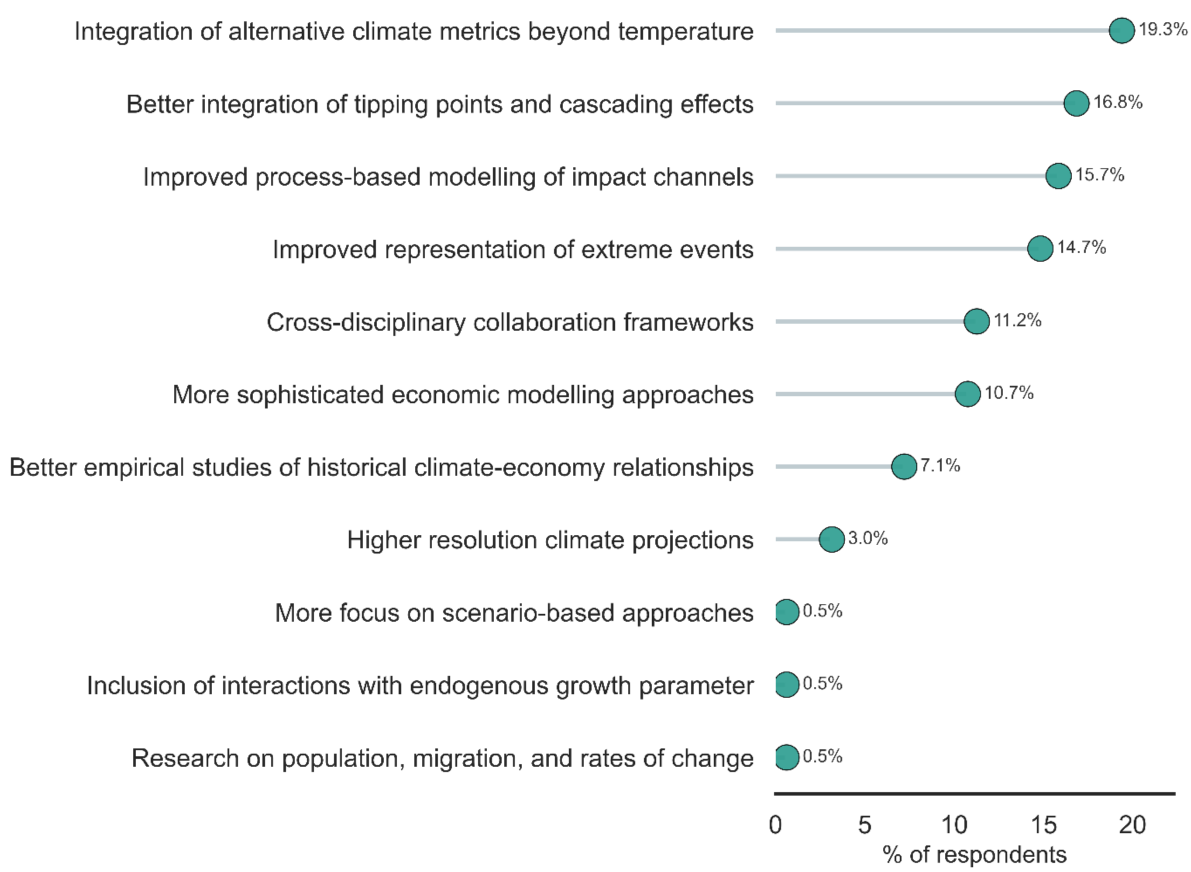

Figure 23. Highest priority research needs identified.

Respondents emphasise the need for better integration of alternative climate metrics beyond temperature, explicit modelling of tipping points and cascading effects, and improved process-based impact channels. Cross-disciplinary collaboration and enhanced representation of extreme events also rank highly.

A recent study (Costanza et al., 2025) warns that institutional and political-economic structures - fossil fuel interests, financial elites, and pro-growth policy paradigms - create a form of societal “growth addiction” that reinforces GDP-centric thinking and slows model reform. Overcoming these barriers requires not only technical improvements but also broader institutional change. Financial sector attention to climate risks is evolving, with institutional investors increasingly adopting sophisticated climate strategies that integrate physical and transition risks (Choi et al., 2020; Moldovan et al., 2024), while monetary policy frameworks (McKibbin et al., 2020) are beginning to shift, but policy instruments like carbon pricing must be designed with public acceptance and equity considerations in mind (Klenert et al., 2020) to enable the systematic transformation that improved damage modelling calls for.

Building on our findings, we propose a three-track approach for the next phase of this work, focusing on improving accuracy, expanding scope, and enhancing decision-usefulness of climate damage assessments.

1. Improving accuracy within damage functions

The survey-based developments presented in Section 3.2 demonstrate pathways for improving aggregate damage functions through better calibration and uncertainty quantification. Priority actions include empirical analysis to calibrate the approach outlined in Section 3.2, through the expert working group (outlined below) and widening the survey to encourage participation from the Global South. This step should be pursued alongside consultation with policymakers, financial institutions, and NGFS stakeholders to establish implementation routes. IAM modelling groups, central banks, and financial regulators should integrate improved damage functions into the next generation of NGFS scenarios, reporting ranges rather than point estimates to better communicate uncertainty. The timeline is immediate to near-term; survey-based developments are already grounded in expert elicitation and can be operationalized within existing IAM architectures.

2. Expanding scope beyond damage functions

Certain impact channels cannot be adequately captured within aggregate damage functions and require complementary bottom-up approaches, as demonstrated by the process-based developments in Section 3.3. Priority actions include establishing a working group of climate scientists, social scientists, and economists to build consensus on synthesizing extreme events, human mortality, and tipping point risks; gathering empirical evidence through calibration to observed impacts and validation against historical events; and determining how to present these analyses to decision-makers. Key unresolved questions include whether process-based approaches can be incorporated into damage functions or must operate alongside them, how stochastic extreme event projections should be visualized, and what communication methods best convey cascading risks to financial institutions. The timeline is medium-term, up to five years for consensus-building, and empirical validation, though progress on individual components can proceed in parallel.

3. Improving communication & decision-usefulness

Even with improved accuracy and expanded scope, climate damage assessments will fail to inform decisions if they cannot be effectively communicated to policymakers and financial institutions. Priority actions include developing a systemic risks dashboard that synthesizes aggregate damage functions, process-based impacts, and scenario narratives into decision-relevant formats tailored to different audiences and time horizons; creating visualization tools using qualitative and visual methods consistent with IPCC guidance (risk registers with traffic light indicators, percentile ranges from ensemble functions, scenario narratives for outcomes outside modelled ranges); and ensuring accessibility across short-term planning horizons (5, 10, 20 years) relevant to financial decision-making, with mortality and human security impacts reported explicitly alongside economic damages.

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The appropriate response is not to wait for perfect models – but to recalibrate governance toward precaution, robustness, and transparency.

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Recommendations for financial regulators and supervisors

1. Climate risk as a financial stability issue

We see strong evidence that climate change amplifies the traditional drivers of financial instability, including macroeconomic downturns, geopolitical tensions, supply-chain disruptions, and destruction of human and physical capital.
Critically, these interactions occur even when global averages might appear moderate. Regional extremes, temporal clustering of shocks, and compounding effects can generate system-wide stress disproportionate to headline GDP impacts.
This supports the view that climate risk is not merely a micro-prudential concern, but a core threat to long-term financial stability.

2. Implications for stress testing and supervision

Our analysis identifies several limitations in current supervisory climate stress tests:

- Over-reliance on mean temperature pathways.
- Use of smooth damage functions that suppress tail risk.
- Point estimates that mask deep structural uncertainty.

To address these weaknesses, we suggest reporting ranges rather than single outcomes in climate stress tests, testing resilience across multiple plausible damage trajectories, and explicitly incorporating non-linearities, thresholds, and compounding mechanisms where possible. Where modelling cannot reliably quantify outcomes, particularly at higher warming levels, supervisors are encouraged to acknowledge limits explicitly rather than allowing false precision to shape risk perception.

3. Tail risk and prudential risk management

A recurring theme in the expert elicitation is that low-probability, high-impact outcomes dominate climate risk. From a prudential perspective, this strongly suggests that median outcomes are insufficient guides to stability alone – as even small probabilities of catastrophic loss warrant attention. On this point, climate supervision should align with actuarial approaches to ruin risk, taking the precautionary principle. Accordingly, our report reinforces the rationale for supervisory approaches that treat climate change analogously to other sources of systemic tail risk, where the objective is not to price risk accurately, but to prevent destabilising outcomes.

Recommendations for Institutional Investors and Pension Funds

1. Fiduciary duty under climate risk

The report directly challenges the assumption that fiduciary duty can be fulfilled through narrow financial metrics alone.

Our elicitation with scientists shows that: climate impacts are cascading and likely to undermine the stability of the societies into which beneficiaries retire, and on which portfolio performance depends. As well as affecting fiduciary obligations, climate damages can undermine the very correlation between GDP growth and asset values. This is particularly relevant for long-horizon investors, whose liabilities extend into periods where climate impacts intensify.

2. Implications for risk assessment and portfolio construction

For institutional investors, the report suggests several concrete shifts:

- Moving beyond reliance on GDP-linked damage estimates when assessing long-term risk.
- Paying greater attention to regional concentration, extreme-event exposure, and correlated shocks.
- Stress-testing portfolios against tail-risk scenarios, not just median temperature pathways.

Our findings also caution that reconstruction-driven GDP growth can mask declining wealth stocks – meaning asset values may deteriorate even as headline economic indicators appear resilient.

3. Diversification meets systemic exposure

Finally, our report underscores that climate risk cannot be fully diversified away. While modern portfolio theory assumes that idiosyncratic risks can be reduced through diversification across assets, sectors, and geographies, climate change increasingly manifests as a systemic risk. Operating through shared physical systems, global supply chains, and tightly interconnected financial networks, climate impacts generate correlated losses that are likely to affect all portfolios simultaneously – particularly at higher levels of warming and economic damage.

As temperature thresholds are crossed and increasingly destabilising impacts arrive, the core assumption of evenly distributed risks becomes untenable, making strategic traditional diversification ineffective and requiring investment practices to evolve.

For large asset owners and pension funds, this reinforces the importance of:

- Engaging with policy frameworks that reduce systemic risk at source.
- Treating mitigation and transition not only as ethical considerations, but as risk-reduction strategies.
- Recognising that portfolio-level adaptation has limits in a destabilised macroeconomic environment.

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Appendix: Technical Details for Direct Damage Function Improvements

This appendix provides complete technical specifications for the three developments presented in Section 3.2, including methodological details, mathematical formulations, and comprehensive results.

Temperature-stratified damage function

Rather than fitting a functional form and extrapolating, we directly elicit climate scientists to estimate economic damages separately at 1.5°C, 2°C, 3°C, and 4°C of warming. These temperature levels correspond to key policy thresholds: the Paris Agreement's aspirational target, its upper limit, current policy trajectories, and worst-case scenarios under continued emissions growth. By anchoring estimates at these specific levels, we can assess whether the smooth polynomial functions used in IAMs accurately reflect expert understanding of damage accumulation (Pretis et al., 2018).

Survey responses reveal that median damage estimates increase more than linearly with temperature, though with substantial variation among respondents. At 1.5°C, the median estimate suggests 10.4% GDP loss with uncertainty ranging from 22.2% loss to 4.1% increase. By 3°C, central estimates reach 34.2% loss, but the uncertainty band widens dramatically to 59.6% loss to 0.9% increase. This expanding uncertainty reflects expert recognition of compounding risks, feedback mechanisms, adaptation limits, and potential tipping points that become increasingly important at higher temperatures (Newell et al., 2021).

The results of the elicitation (Figure 10) emphasise the overall trajectory of damages implied by the survey: a near-linear rise in central estimates combined with an exponentially widening uncertainty band. The widening range reflects expert recognition of compounding and nonlinear risks, including feedbacks, adaptation limits, and tipping points.

The widening uncertainty at higher temperatures challenges a fundamental assumption in climate economics. Standard IAM practice treats uncertainty as roughly constant across temperature ranges, applying symmetric error bars or probabilistic distributions that don't change shape with warming level. Expert judgment suggests the opposite: we become less certain about outcomes as we move further from observed climate conditions (Pindyck, 2013, 2017).

Comparison with existing damage functions reveals systematic patterns. The Nordhaus DICE model (Nordhaus, 2008, 2017), which has anchored climate policy analysis for decades, suggests that damages are 3 .1% of global income at 3°C – predicting a less than 0.1% fall in the rate of annual economic growth. The updated empirical analysis (post retraction) by Kotz et al. place income reductions of 17% in 2050, ,equivalent to annual growth reduced by approximately 0.6 percentage points (from an annual growth rate of 2.0% to 1.4%). Howard and Sterner's calibration suggests 7-8% reductions for non-catastrophic damages (roughly 0.3 percentage points lower annual growth) and 9-10% when factoring in catastrophic risks (approximately 0.4 percentage points). Meta-analyses show damage estimates vary by more than an order of magnitude depending on methodology (Tol, 2024). Expert median estimates fall above this range, but with notably wider confidence intervals than any individual published function assumes. This uncertainty partly reflects fundamental challenges in forecasting long-run economic trajectories (Christensen et al., 2018).

The divergence is particularly pronounced at temperatures above 2°C. Where standard functions assume smoothly accelerating damages, expert judgment suggests the possibility of more abrupt transitions. 56% of respondents indicated damages could exceed 40.8% at 4°C, a level that would represent near-complete economic disruption. This heavy tail in the distribution captures concerns about threshold effects, system failures, and cascading impacts that polynomial functions cannot represent.

Collapse threshold probability distributions

This development introduces the concept of an adaptation threshold - a temperature beyond which modern economic and social systems cannot maintain functionality - and uses expert judgment to estimate where this critical point occurs (Kolstad et al., 2014).

We asked survey respondents to identify the temperature threshold beyond which they believe economic collapse becomes likely. The question was framed carefully: not human extinction, not the end of all economic activity, but the breakdown of modern interconnected economic systems as we know them. Responses could include "no threshold exists" if respondents believed adaptation could continue indefinitely.

Survey respondents provided subjective temperature thresholds beyond which they believe modern economic and social systems could fail to function. The resulting cumulative distribution (Figure 8) indicates rising risk beyond ~3°C and substantial uncertainty across respondents. This supports the focus on linking damage functions with collapse probabilities rather than assuming damages grow smoothly and indefinitely. It also highlights that experts interpret climate risk as fundamentally nonlinear and dominated by tail-risk dynamics. Although, a small number of respondents suggested that there will be no collapse.

The resulting probability distribution reveals substantial variation but clear patterns. The median collapse threshold occurs at 4°C, with the 25th-75th percentile range spanning 2.5-4°C and 4-6°C, respectively. Notably, 36% of respondents identified a threshold below 4°C, suggesting that scenarios commonly modelled in IAMs may venture into territory where economic continuation is questionable. Only 7% indicated that no collapse threshold exists, arguing that adaptation can always find solutions regardless of warming level. Recent analysis of catastrophic climate scenarios highlights that current risk assessments systematically neglect the potential for societal collapse at these temperature levels, representing a critical blindspot in climate policy (Kemp et al., 2022).

The cumulative probability distribution shows risk accelerating rapidly beyond 3°C. At 3.5°C, 9% of experts believe collapse becomes probable. By 4°C, this rises to 14%. The sharp rise in the cumulative curve indicates that while experts disagree about the precise threshold, most cluster their estimates in the 3-5°C range rather than distributing evenly across all possibilities. This pattern supports framing climate damages in terms of tail risk rather than smooth trajectories. Financial institutions understand Value-at-Risk and probability of default - concepts that translate directly to collapse thresholds.

The implications for functional form selection are significant. Standard quadratic or cubic polynomials cannot represent collapse thresholds - they grow smoothly without bound. Alternative forms are needed. Logistic functions saturate at 100% damages, providing a natural upper bound. Weitzman-style specifications with singularities at a critical temperature explicitly incorporate collapse thresholds. Piecewise functions can show sharply accelerating damages beyond a threshold temperature. We explore different functional forms in the next development.

It must be acknowledged that this remains exploratory as the concept of "economic collapse" is not precisely defined, and expert interpretations varied.

Functional form comparison

Constraint 1: Historical calibration

We first compare multiple functional forms fitted to observations against each other (Figure 12, left panel). We fit seven functional forms - quadratic, exponential, power law, logistic, Gompertz, polynomial, and Weibull - to disaster/GDP observations as presented by Keen (2023). These observations span the temperature range experienced since 1900, capturing the relationship between warming and economic damages where we have direct empirical evidence.

All seven functional forms fit the disaster data with nearly identical accuracy. R^2 values range from -0.05 to 0.09, indicating that none of the specifications explain more than 9% of variance in the observed data. This is not a failure of the modelling - it reflects genuine scatter in how disasters affect economies, where temperature is only one of many contributing factors. Within the observed range (0.2-1.0°C, left panel), the functions are visually indistinguishable, all passing through the centre of the data cloud. When these identically fitted functions are extrapolated beyond the observed range without additional constraints, they diverge dramatically. At 3°C warming, damage estimates without collapse constraints range from 1.5% (power and polynomial) to 87% (Gompertz) of GDP - a 58-fold difference (Figure 13). This extreme divergence arises entirely from differences in how each functional form accelerates beyond the fitted range. The Gompertz and logistic functions, which naturally approach asymptotic limits, produce the highest damages. The power, polynomial, and quadratic forms remain relatively flat, producing unrealistically low estimates. The exponential and Weibull functions occupy intermediate positions.

This initial analysis reveals a critical problem: functions fitted only to low-temperature observations produce implausible extrapolations. Power and polynomial forms suggest 3°C warming would cause less than 4% GDP loss - inconsistent with expert understanding of climate impacts and physical evidence of system thresholds. Conversely, some S-curve forms (Gompertz, logistic) suggest near-total economic collapse at 3°C even though they're constrained to approach 100% asymptotically at much higher temperatures. The wide range (1.5% to 87%) and implausible extremes indicate that historical calibration alone is insufficient - additional constraints are needed to produce physically meaningful projections.

Constraint 2: Expert collapse thresholds

We then address this limitation by using expert judgment data to constrain the fits (Figure 12) and identify which mathematical specifications best capture the damage trajectory implied by climate scientists' expectations. We constrain each function to reach 100% economic loss at temperatures identified by climate scientists as plausible collapse thresholds. Expert elicitation reveals substantial uncertainty: the 10th percentile collapse threshold is 2.1°C, the median is 3.4°C, and the 90th percentile is 5.4°C. This distribution reflects genuine scientific uncertainty about the temperature at which Earth system feedbacks trigger catastrophic economic disruption.

It is important to clarify what "100% economic loss" means in this framework. GDP measures annual economic flow (goods and services produced per year), while capital stock—the physical infrastructure, buildings, and equipment that generate this flow - is typically valued at 3-4 times annual GDP. Complete destruction of capital stock would therefore represent damages of 300-400% of annual GDP. Our "100% GDP loss" constraint represents the cessation of measurable economic activity as conventionally defined, not necessarily the complete physical destruction of all capital. At collapse thresholds, climate impacts may render existing capital stock unusable (agricultural land too hot for crops, infrastructure repeatedly destroyed by extreme events, energy systems unable to function) even if not physically obliterated. This flow-based definition aligns with how damage functions in integrated assessment models conceptualize economic impacts, though it underscores that framing damages solely as GDP percentages obscures the deeper question of whether capital stock can continue generating economic output under extreme climate conditions.

Ensemble generation

For each functional form, we optimize parameters at five different collapse thresholds (10th, 25th, 50th, 75th, 90th percentiles) by minimizing a combined loss function:

$$\text{Loss} = w_1 \times (\text{fit to data}) + w_2 \times (\text{deviation from 100\% at collapse})$$

This produces 35 damage trajectories (7 functions x 5 collapse thresholds) where each is fitted to satisfy both constraints simultaneously. Unlike simple scaling approaches, this method allows the optimization to find parameters that balance both requirements - or to fail, revealing which combinations are physically implausible.

Not all functions can satisfy both constraints at all collapse thresholds. When forced to reach 100% at very early collapse temperatures (2.1°C or 2.7°C) while still fitting observed disaster data, some functions produce damages exceeding 100% of GDP at intermediate temperatures like 3°C. This incompatibility is not a modelling failure - it reveals that certain functional forms are inconsistent with catastrophic early-collapse scenarios. It is worth noting, however, that damages exceeding 100% of annual GDP are not inherently implausible: capital stock is typically valued at 3-4 times annual GDP, meaning that sufficient capital destruction could indeed exceed one year's economic output.

Zero functions are compatible with p10 collapse (2.1°C) or p25 collapse (2.7°C). All 7 functions are compatible with p50-p90 collapse (3.4-5.4°C): Plausible damage trajectories. This demonstrates that if collapse occurs below 2.7°C, none of the standard functional forms used in climate economics can reconcile observed disaster impacts with catastrophic outcomes - a finding that constrains plausible scenarios. Using the median expert collapse threshold (3.4°C), all functions produce plausible damage estimates ranging from 43% to 88%.

The key finding is not that one functional form is definitively "correct" - we lack data at 3-4°C to validate any specification empirically. Rather, the choice of functional form matters enormously for high warming scenarios, and expert judgment provides a tool for discriminating among alternatives. Where historical temperature data covers at most 1°C of variation, expert understanding synthesizes physical, biological, and social science knowledge about how systems respond to large temperature changes. The ensemble reveals three critical insights:

1. Historical data cannot discriminate among functional forms: All functions fit Keen disaster observations with $R^2 < 0.1$, explaining less than 10% of variance. The high scatter reflects genuine complexity in how disasters affect economies.
2. Expert collapse thresholds provide essential constraints: Without upper bounds from physical understanding, purely statistical fits produce implausible extrapolations. The collapse constraint grounds projections in scientific judgment about system limits.
3. Uncertainty is irreducible through more data: Even perfect knowledge of disaster impacts at 0.2-1.0°C would not resolve the 14-fold uncertainty at 3°C. The divergence arises from extrapolation beyond observed conditions, not from parameter estimation error. This is structural uncertainty about system behaviour under unprecedented stress.

The ensemble approach should replace single-function specifications in climate risk assessments. For NGFS scenarios and banking stress tests, we recommend:

1. Report ranges, not point estimates: At 3°C, damages span 44-88% (median threshold) or 6-88% (full compatible range). Single-number projections provide false precision.
2. Test decision robustness across ensemble: Investment strategies, policy choices, and risk management frameworks should perform acceptably across the full ensemble, not just for a preferred specification.
3. Acknowledge compatibility constraints: Functions that cannot satisfy both historical data and expert thresholds reveal physical impossibilities. Early-collapse scenarios (<2.7°C) are incompatible with observed disaster patterns.
4. Maintain dual constraints: Future work should continue requiring functions to match both empirical observations and expert-informed system limits. Neither alone is sufficient.

Summary: Synthesizing expert judgment into implementable damage functions

Developments 1-3 each address specific limitations of current damage functions, but implementing them separately risks inconsistency across IAM implementations. We therefore present an Expert-Calibrated Damage Function (ECDF) that synthesizes all three approaches into a unified probabilistic framework directly implementable in NGFS scenarios.

Rather than selecting a single deterministic damage function $D(T)$, the ECDF is a probability distribution over damages:

$$D_{ECDF}(T) = \sum_{f} P(f \mid \text{data}) \cdot D_f(T \mid \theta_f)$$

where each functional form f contributes proportionally to how well it matches expert judgment. This Bayesian approach incorporates three uncertainty sources: parameter uncertainty (experts disagree on damage magnitudes), structural uncertainty (no consensus on functional form), and learning over time (posteriors update as evidence accumulates).

The ECDF integrates the three developments. Development 1's temperature-stratified estimates serve as calibration targets, fitting parameters θ_f for each functional form at 1.5°C, 2°C, 3°C, and 4°C rather than extrapolating from limited historical data. Development 2's collapse threshold distributions provide upper bounds, constraining damage functions to respect system limits and ensuring $D(T) \rightarrow 100\%$ as temperatures approach 4°C. Development 3's functional form comparison determines posterior weights $P(f \mid \text{data})$, with forms matching expert judgment receiving higher probability in the ensemble.

Implementation follows six steps: specify candidate forms (quadratic, exponential, logistic, etc.); fit each to Development 1 estimates; apply Development 2 collapse constraints; compute posterior probabilities based on goodness-of-fit; generate the ensemble as probability-weighted average; and report percentile ranges (10th, 50th, 90th) capturing uncertainty. This provides financial institutions with the full damage distribution needed for stress testing rather than misleading point estimates.

The ECDF offers key advantages over current practice: explicit transparency in assumptions, flexibility to update as evidence emerges, proper uncertainty quantification through probability distributions, multi-model consistency across IAMs, and systematic incorporation of expert knowledge. However, important limitations remain. Expert judgments may be biased, the functional form set is somewhat arbitrary, and the framework treats all temperature levels symmetrically despite varying expert confidence. Most fundamentally, the ECDF addresses only aggregate temperature-GDP relationships, maintaining the top-down macroeconomic perspective that workshop participants identified as insufficient.

These survey-based developments represent a damage function using temperature-stratified calibration, bounded by collapse probabilities, weighted across multiple forms, and updated through Bayesian learning could be operational in NGFS scenarios within months. However, workshop participants emphasized mechanisms that cannot be captured in aggregate functions no matter how sophisticated the calibration: capital destruction, labour productivity losses, sectoral heterogeneity, extreme event volatility, and adaptation dynamics. Section 3.3 presents developments demonstrating these complementary process-based approaches essential for comprehensive climate risk assessment.

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